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Software Defined Grid

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SUMMARY

Softwarization has been transforming industries like data center and communications businesses. The established hardware-based architectures are being replaced by fundamentally new approaches - software-based systems which are essentially more flexible, dynamic and powerful. In this paper we analyse the evolution in data centers and communications networks towards virtualized platforms and study how a similar type of evolution could impact and benefit power distribution. Following the softwarization process in other industry sectors, we consider that next a Software Defined Grid (SDG) will emerge.

KEYWORDS

Softwarization, cloudification, software defined networks, data centers, 5G networks

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1 INTRODUCTION

Softwarization has transformed industries like data center and communications businesses. Key drivers for this transformation have been better adaptability, increased flexibility and reduced costs.

The basic building blocks of data centers and communications networks have been redefined. Purpose built vendor specific hardware that runs vendor specific software, has been replaced by commoditized hardware and standard computing resources. Differentiation is provided by the software running on that commodity hardware. The software is not tied to any specific hardware supplier. Instead, customers pick best of the breed software, which in some cases is open source. Customers also replace the software depending on evolving needs and update it periodically to include new functionality. Virtualization, container and cloud technologies are used for increased flexibility and elasticity to adapt the application to the service requirements in terms of capacity or computational needs.

Smart grids are evolving to enable extensive integration of distributed generation based on renewable energy sources. The default value chain in smart grid is changing to include facilities and consumers as active players contributing to the energy generation and power balance. Information and communications technologies are increasingly used to monitor and control the power grid and its devices. So far power grid management has mostly been physically separated from other information and communications systems. Dedicated, in-house computing environments and communications networks have been used. Going forward the power grid itself and its key building blocks could undergo a similar type of change to the one that has taken place in data centers and communications networks. Therefore, similar softwarization process might lead to a Software Defined Grid (SDG).

This paper studies the underlying concepts in softwarization and how the evolution in data centers and communications networks has taken place. The paper further outlines how the similar type of evolution could impact power grids and what kind of benefits it could bring. In addition to technical aspects, the limitations, cost structures and business models are discussed as well.

The paper is structured as follows. Section 2 studies the concepts in softwarization. Sections 3 and 4 explore how these concepts have transformed data centers and cellular networks, respectively. Section 5 investigates how similar type of transformation could apply to power networks, particularly to distribution networks. In this section, a model for Software Defined Grid is presented. This is followed in Section 6 by a comparison of Software Defined Grid and the traditional power grid. Section 6 also discusses challenges and limitations of Software Defined Grid. Finally, Section 7 provides a summary and conclusions.

2 SOFTWARIZATION

The key underlying concepts in softwarization include virtualization, virtual machines (VM), network function virtualization (NFV), software defined networking (SDN), clouds, fog computing, edge computing, containers and commoditization of hardware like computing platforms, radios and switches, Fig. 1.

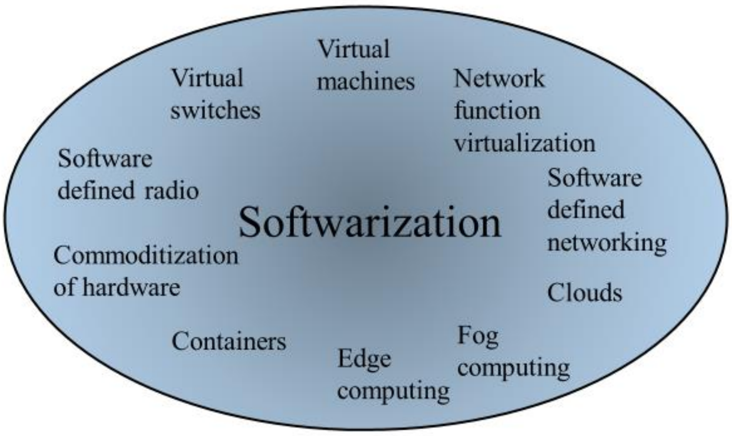

Figure 1: Softwarization concepts

Virtualization refers to the fact of isolating underlying computer hardware from applications that share physical computer resources in a flexible manner. The goals behind virtualization are to increase computer resource utilization, efficiency and scalability [1].

In a traditional computer, the operating system (e.g. Linux, Windows) runs on dedicated hardware. The operating system provides a platform to run software applications that implement specific functionality. In a virtualized system a hypervisor is running on top of the operating system. Hypervisor provides the virtualization platform on top of on which the virtual machines are running. Virtual machines are software entities emulating a complete computer environment consisting on the hardware and operating system. The software applications previously running on top of the operating system on dedicated hardware, are now run on the virtual machines. Virtual machines can be flexibly started and stopped as needed. Likewise, computing resources like storage and memory can been allocated as needed. Virtual machines can emulate various operating systems which can be different from the operating system running on the actual physical hardware [2].

Following same virtualization concept in traditional computers, Network function virtualization (NFV) decouples network services. For example, firewalling and NAT (Network Address Translation) that previously run on top of dedicated, purpose-built devices, can be virtualized as network services. These network services can be run as Virtual Network Functions (VNFs) on general purpose computing platforms and often on virtual machines [3].

The same paradigm of virtualization applied to network functions can be applied to network switching and routing with the Software defined networking (SDN). The SDN decouples (a) data forwarding (forwarding plane) and (b) control of data forwarding (control plane). For example, instead of having complex, purpose-built routers and switches running hardware manufacturer specific software, forwarding is done by more straightforward devices. Control software is implemented as smart controllers controlling multiple forwarding devices. Smart controllers are running on general purpose, computing platforms and often on virtual machines [3].

As indicated in [3] NFV and SDN are complementary technologies capable of providing an overall networking solution: “SDN can provide connectivity between Virtual Network Functions (VNFs) in a flexible and automated way, whereas NFV can use SDN as part of a service function chain”. An important function needed to achieve the flexibility enabled by NFV and SDN is the management solution also knowns as the orchestrator.

Ref. [4] defines cloud as “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction”. It further defines on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service (metering capability) as essential cloud characteristics. The most common cloud types are public clouds, private cloud and hybrid clouds [4],[5]. Amazon Web Services (AWS), Microsoft Azure, and Google Cloud are examples of public clouds. They service a large number of customers of various size and provide a broad set of readily available tools for application development and management. The term private refers to a cloud provisioned for a single organization. The difference to an organization specific traditional in-house data center is that capacity is allocated to applications, or workloads, elastically and orchestrated in a similar manner than in public clouds. Hybrid cloud is a combination of public and private clouds. Applications can be dynamically orchestrated between the two platforms. Lately all the three previously mentioned large public cloud providers have launched their hybrid cloud offerings. Organizations can elastically run part of their applications on on-premises computers behind firewalls and part in Microsoft’s, Amazon’s or Google’s public clouds.

Fog computing, a term introduced by Cisco, extends cloud computing capabilities to the edge nodes of the network [6],[7]. Among these edge nodes are base stations, routers and switches. Multi-access Edge Computing (MEC) is a term similar to fog computing. As a concept it is more limited as it primarily focuses on the cellular networks [6].

Traditional data center applications typically follow client-server architecture. Applications are split into two tiers – one running in the workstation and the other on server. These two parts are tightly coupled - the server components exist only for the client components and vice versa. Cloud applications on the other hand typically follow service-oriented architecture (SOA). SOA breaks applications into components which are there to serve multiple type of clients.

In recent years containers have become a popular way to implement the SOA architecture. An application (software) container market for selling and buying functionality has emerged. Service components are running inside software-based containers which share the same operating system resources without need for a separate virtual machine (VM). As a consequence, the container-based applications are generally more efficient than virtual machine-based ones. Containers can also be easily moved between different hosts. But containers do not offer possibility to run different operating systems as virtual machines do. Dockers is a popular platform to create containerized applications [2],[8].

While the role of software has increased, hardware has become a commodity. Brand hardware has been replaced by inexpensive, straightforward blades and motherboards resembling each other. Ref [9] forecasts that this evolution will continue and so called hyperconverged integrated systems, HCIS, will emerge. These offer “shared compute and storage resources, based on software-defined storage, software-defined compute, commodity hardware and a unified management interface”. Capacity can be allocated when needed by utilizing self-service model.

Software defined radio (SDR) and virtual switches provide other examples of commoditization of hardware. In software defined radio modulation and coding are performed digitally as the traditional way has been to use specialized components. [10]. Open switches, e.g. Open vSwitch, are virtualized software-based switches. Depending on the implementation they can run on hypervisors in virtualized environments or as control software for commodity switching hardware [11].

3 EVOLUTION IN DATA CENTERS

According to Gartner, a global research and advisory firm, “by 2025, 80 percent of enterprises will migrate entirely away from on-premises data centers with the current trend of moving workloads to colocation, hosting and the cloud leading them to shut down their traditional data center” [12]. Gartner says, year 2018, that already 10% of enterprises have closed down their traditional data centers [13]. This “does not necessarily mean that everything would be going to the cloud, but IT leaders do need to start thinking about where current and future workloads will live based on business reasons” [13]. Gartner further states that “Organizations need to create an environment that houses more agile infrastructure both on-premises and in the cloud” [13] and that “Leaders must identify whether there are truly strategic reasons to persist with on-premises needs, especially when they consider the significant amount of investment involved is often amortized over many years” [12]. According to [14] “the data center is being repurposed. Some workloads are going to public cloud providers, while others are being assigned to the data center”. Ref. [14] recognizes edge computing, hybrid clouds and containers as trending data center and cloud technologies.

Ref. [15] defines a virtualized data center (VDC) as ”a data center where some or all of the hardware (e.g., servers, routers, switches, and links) are virtualized”. Ref [15] and [16] divide virtual data center network into multiple levels as visualized in Fig. 2 (a): Applications or workloads run in the cloud computing layer on top of a distributed virtual machine layer. The two top layers utilize resources on the physical data center network (DCN) layer, which consists of physical computing, storage and networking devices. All these three levels are managed and orchestrated elastically, on on-demand basis.

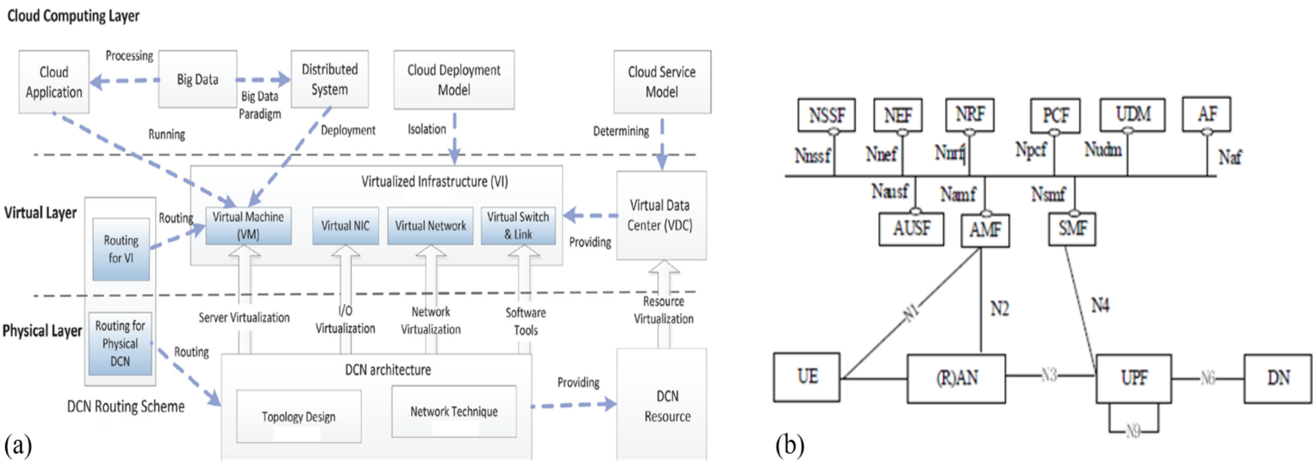

Figure 2: (a) Cloud computing network architecture for virtual data centers [16]
(b) 5G System architecture [19]

4 EVOLUTION IN CELLULAR NETWORKS

Emerging 5G cellular networks are building on the success of preceding 3GPP (3rd Generation partnership Project) cellular network generations. 5G is specified in releases Rel-15 and Rel-16. The Rel-15 was completed 2018 and Rel-16 is expected to be completed by the beginning of 2020. 5G is the first cellular network generation which clearly targets industrial applications along with traditional consumer market [17].

Earlier cellular network architectures basically defined dedicated hardware entities and interfaces among these entities. 5G is inherently based of softwarization. As Ref. [18] states: “The notion of network virtualization concentrates on the concept of a software-based representation of both the hardware and software resources considering both data and/or control-plane functions". 5G network architecture is built on service-oriented architecture, called Service based architecture (SBA) in this context. Fig. 2 (b) depicts the key components of the 5G architecture [19]. The essential control plane functions consist of Access and Mobility Management Function, AMF, and Session Management Function (SMF). These utilize services which are connected to a bus-like structure as shown in Fig. 2 (b). Network Slices Selection Function NSSF is an example of a service -ased functionality where network resources are allocated to network slices associated to different mobile devices. All these functions are virtualized network functions (VNFs) that can be deployed in a cloud environment. The bottom part of the picture denotes the data plane. User Plane Function (UPF) is similarly a VNF that can be deployed in cloud environment to manage the mobile data plane. The number of VNFs can be elastically changed as needed. This enables creation of specific instances for certain industries, e.g. smart grids, or specific users, e.g. a power grid operator. These specific instances are called network slices. UE denotes the User Equipment, e.g. a mobile phone or a sensor. R(AN) denotes the radio access network, and to the data network (DN), e.g. public internet. Software defined networking (SDN) orchestrates connectivity between VNFs and in the (R)AN.

5 ARCHITECTURE OF SOFTWARE DEFINED GRID

In this section we evaluate the impact of the softwarization concepts introduced in section 2 when applied to power grids. Fig. 3 outlines potential architectural principles of Software Defined Grid. Power grid switching devices and measuring devices are clearly separated from the software controlling them. The software runs in the cloud in software containers or alternatively in a virtualized environment. Software containers are placed either in close proximity to the switching and measurement units, or more centralized in the cloud depending on the functionality they provide. Application functionality, e.g. for the power flow solution for the whole grid, is divided into multiple containers which interact with each other according to the principles of service-oriented architecture (SOA). Applications and containers are managed on grid level by a container-orchestration system, e.g. Kubernetes.

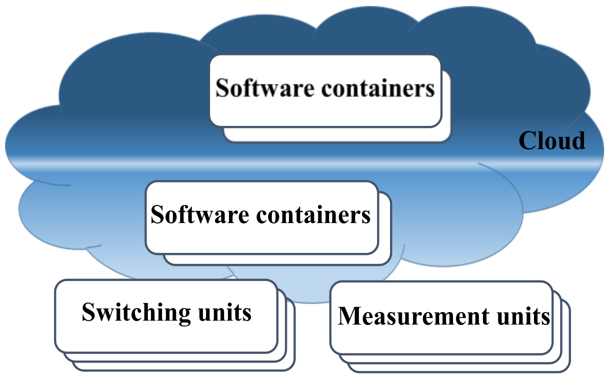

Figure 3: High level architecture of Software Defined Grid

Next we look at substation level, at secondary substation level and ultimately power grid level in more detail. On substation level commoditization of hardware will mean that switching devices, e,g. circuit breakers, and measurement units like sensors would be relatively similar and not providing too much differentiation. Network function virtualization (NFV) and software defined networking (SDN) would mean that control and data processing is moved to separate control entities. This evolution has already partly been taking place in power grids due IEC 61850, IEDs (Intelligent Electronic Devices) and introduction of optical LANs at substations [20]. But currently both IED hardware and software is coming from power grid device, e.g. switching device manufacturers. Going forward, due to commoditization of hardware these control entities would be running on standard inexpensive blades and motherboards. Control entities would be containers, or alternatively virtual machine (VM) based applications, which can be flexibly created and moved. A common software tool would exist to configure all control entities. At present, system and IED configurator tools are typically hardware vendor specific. Fig. 4 illustrates a primary station in Software Defined Grid.

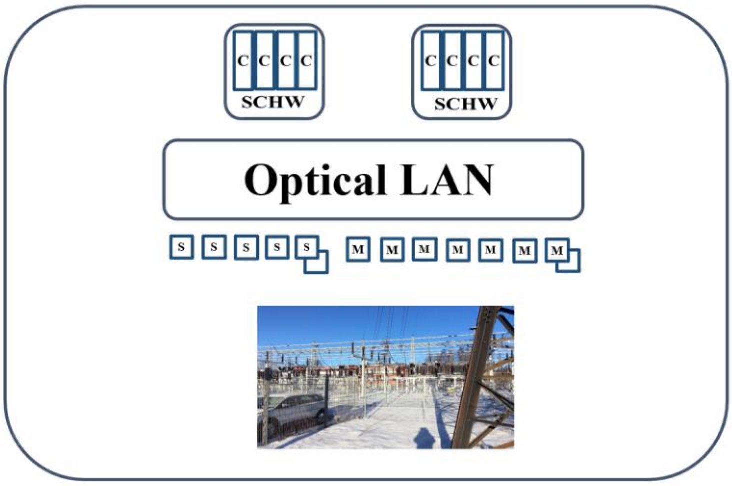

Figure 4: Software defined primary substation
(SCHW = standard computing hardware, C = Container, S = Switching, M= Measurement)

In secondary substations (distribution transformer stations) the controlling network virtual functions (NFVs) would be running in containers on standard small-scale computing platforms, e.g. Raspberry Pi. Commoditized measurement devices (sensors) and switching devices are directly connected to computing platform typically through an Ethernet connection. The similar evolution would apply to other smaller distribution grid sites like disconnector stations, small and medium scale distributed generation sites, and facilities providing e.g. demand response functionality.

On grid level, as depicted in Fig 5. cloud and fog computing will provide the dynamic platform interconnecting controlling, managing and analysing software and commoditizing power grid devices. All controlling, managing and analysing software is in containers which can be flexibly allocated inside the cloud and fog. The fog (cloud edge) allows real time operation and increases reliability as it can also operate off-line. It enables pre-processing and data buffering for the increasingly voluminous data gathered from the grid. It also increases security as it creates a separation layer towards the switching and measurement devices.

Containers on cloud level facilitate grid level view, e.g., power flow. They also provide grid level control and steer containers running on substation level. A very important function for grid level containers is to analyse the continuous flow of information coming from the network. This task is made more efficient by numerous readily available cloud tools, e.g., Microsoft Databricks [21], Amazon Kinesis and Google Dataflow.

A common information model is required to enable communication between containers, switching units and measurement units. Power grids are relatively well positioned for this requirement as there are already well established and deployed standards in this area. The most significant ones are IEC CIM and IEC 61850 [22]. These standards are partially overlapping and incompatible though [22]. IEC CIM has a broad application area while IEC 61850 is focused on substation automation.

Power grids are highly critical to the modern society. Consequently, security is highly important. Softwarization will introduce challenges, which must be addressed in terms of security and reliability. At the same time softwarization also provides some advantages. Challenges are often related to communication networks and multitenancy, i.e. ultimately sharing the same computing platform with other users. Tunnelling, public key encryption and network slicing are means to address communications security. Concerns related to multitenancy can be addressed e.g. by using hybrid clouds. The most critical, e.g. control related applications could be located in the private part of the cloud. Extensive data analytics for planning and forecasting purposes could be run in the public part of the cloud where computing capacity can be elastically allocated as needed. Advantages provided by cloud environments include the fact that they are run by large enterprises as their primary business, so they are well maintained and operated. Thus, the cloud environment including facilities, equipment, applications, processes and staffing are on a level which is hard for a smaller or medium size company to match. Ref [23] also points out that "software defined networking (SDN) and network function virtualization (NFV) have the potential to reshape the landscape of cyber security for IoT (Internet of Things) system". SDN enables unified security management for switching units and measurement units (sensors) and NFV and network slicing inherently provide separation of users.

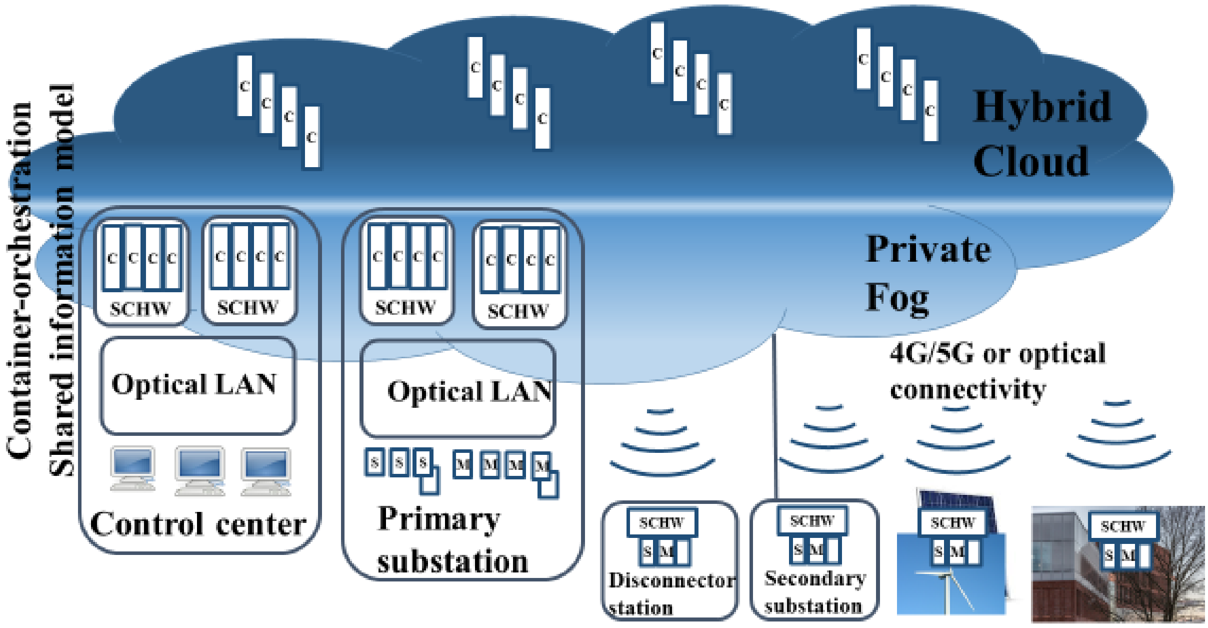

Figure 5: Software Defined Grid

6 COMPARISONS AND LIMITATIONS

Table I summarizes the differences of technical characteristics between the traditional grid and Software Defined Grid.

TABLE I. COMPARISON OF THE TRADITIONAL GRID AND SOFWARE DEFINED GRID

	Traditional power grid	***Software defined grid***
Hardware and software integration	Power grid devices and related software integrated	Power grid devices and related software separated
Computing platforms	Purpose built computing platforms	Standard computing platforms
Allocation on computing resources	Fixed statically allocated computing resources	Cloud based solution: on-demand network access to a pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort
Communication links	Dedicated communication links	Shared communication links
Data storage	Dedicated data storage	Shared data storage

In the introduction we mentioned that key drivers behind softwarization are adaptability, increased flexibility and reduced costs. Adaptability and flexibility are achieved by separating power grid hardware from the related software, by utilizing standard computing platforms and by running the applications as containers in the elastic cloud. This separation enables that modifications can be done by orchestrating a suitable set of software containers according to the changed needs. Cost savings can be achieved by utilizing standard computing platforms and running software containers on them. Let's consider a substation having 20 feeders. Every feeder has a circuit breaker and a protection relay controlling it. In Software Defined Grid the twenty protection relays would be replaced e.g. by two Linux-computers running protection functionality in software containers. There would be two computers for increased reliability.

Sharing of communications links and sharing of data storage will introduce security challenges. These must be addressed as discussed in section 5. In terms of security the most critical parts of the grid are those there the impact of a cybersecurity attack is always system wide or far reaching: control centers, the transmission network, large generation a sites and central nodes in the distribution grid. As pointed out in section 5, Software Defined Grid also provides some advantages related to security. Centralized orchestration can provide more consistent security solutions compared to distributing security components in numerous devices. Due to resource sharing, the facilities, equipment, applications, processes and staffing in cloud environments are on a level which smaller or medium size companies hardly can afford if implemented as in-house systems. Due to resource sharing, performance levels in particular in radio channels needs to be addressed. This can be done e.g. by network slicing and appropriate priorities. It should be noted that public safety networks, providing communications for services like police, fire and ambulance, are increasingly being based on commercial networks [23]. Traditionally public safety organizations have deployed their own dedicated networks, e.g. based on TETRA technology. 3GPP has included functionality already in 4G LTE (Long-Term Evolution) to address public safety availability and security needs. Regarding performance, distribution of functionality to containers needs to be carefully considered in order to avoid excessive communications between some containers.

In current electric power grids controlling, managing and analysing software. e.g., the so-called SCADA (Supervisory Control And Data Acquisition) systems are typically non-cloud systems built to run in isolated, non-vulnerable environments on dedicated communications networks. The same applies to communication within the primary substations and between the primary substations and central SCADA systems. This communication is typically based IEC 61850, IEC 60870 and proprietary protocols and utilization of dedicated communications links. In case there is access to secondary substations (distribution transformer stations) and to disconnector stations, this access can already today be based on public cellular networks by utilizing e.g. private Access Point Names (APNs). The other typical solution is utilization of power grid operator specific radio solutions and separately licensed, dedicated frequency bands. Thus, some elements of Software Defined Grid can be seen in disconnector station and secondary substation communication and early sensoring (IoT) trials [21]. Software Defined Grids would enhance public network-based communications to cover overall connectivity in the electric power grid, including also primary substations, control centers and small and medium scale distributed generation sites. The controlling, managing and analysing software would utilize less expensive yet more scalable technologies and power grid gear would transform to run on commodity hardware.

Not only is sofwarization changing the power grid and its components but it will also reshape the industry. All major disruptions enable new ways of differentiation and new value-added services. They also pave the way for new entrants [25]. Microsoft, Amazon and Google have heavily influenced data center business. In communications industry, as mentioned, 5G is the first cellular generation targeting industrial segment along with the traditional consumer market. Consequently "5G is expected to facilitate a business ecosystem, enabling innovative services and networking capabilities not only for consumers, but also for new industry stakeholders" [18]. Ref. [18] continues "verticals (could) offer a variety of services to a non-telecom specific industry, exploiting network and cloud resource from network operators and cloud providers. Most of the new growth is anticipated in taking place through digitalization of the vertical industries such as factories, transportation and health care." This could mean that new entrants will emerge offering 5G networking services and 5G based applications. This could be either based on spectrum acquired from traditional cellular network operators or on utilizing industry specific frequency bands and/or unlicensed bands.

Software Defined Grid will change power grid technology provider business. Hardware dominated business will transform to software business. In this process there are multiple potential new and changed roles:

- Purely software focused companies will emerge or strengthen their position. These will provide container-based functionality. Customers pick best of breed functionality in containers and also change it more frequently based on evolving needs.
- Some of the established power grid technology suppliers transform themselves to software companies integrating offerings of their competitors into their product and service portfolio.
- Totally new entrants might rapidly be introduced. Companies like Google, Amazon, Microsoft and Facebook have transformed multiple businesses. Some of these have already for long time been working on entering the changing the automotive and transportation business [26]. In the same way as Internet of Vehicles might emerge, we might also see also Internet of Energy.

7 CONCLUSIONS

Sofwarization is a strong trend impacting many industries. In this paper we studied how it has transformed data centers and cellular networks and what this kind of an transformation could mean in power grids. Also e.g. manufacturing is undergoing the same type of change. This evolution is known as Industry 4.0 [27], [28]. We claim that similarly a Software Defined Grid could emerge. It could potentially significantly reshape power grid technology provider business. Resources sharing and shared connectivity imply also challenges related to security, reliability and performance. These must be addressed in order to be able to benefit from adaptability, increased flexibility and reduced costs enabled by softwarization.

Evolution towards Software Defined Grids is made more likely as smart grids must combine traditional power grid technologies with already softwarized communications and information technologies to create a sustainable electric energy system.

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