Smart Grids in mobile fleet operations

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Abstract

In a mobile industrial fleet application different machinery is powered by each its own reciprocating internal combustion engine. EKU Power Drives (EKU) is focusing on increasing the energy efficiency of these fleet applications.

Therefore, the combustion engines are enhanced to mild hybrid units and connected to a smart grid. This semi-automated fleet setup allows to dynamically share load between units or manage the usage of equipment to streamline operational procedures. Single combustion engines are entirely replaced by electric drives and powered by the excess power of the remaining hybrid engines and the grid. The increased load on the remaining engines results in specific fuel consumption advantages. This increases the efficiency of the entire fleet. Economically the achieved fuel savings are only a portion of the gained benefits. On the fleet perspective the necessary number of engines has been reduced and the individual load on the remaining has increased. Operators' biggest cost savings result from less different engines to maintain and store spare parts.

With the power need of the grid and the capability of the electrified auxiliary engine drives, concepts for electric motors and batteries are defined. A suitable net topology concept is developed, and the independent grid is controlled by a distributed cooperative closed loop control. This enables a configuration-less connection setup between different machinery of the fleet.

1 Introduction

In off-grid, high horsepower off-highway and industrial applications (i.e. tug boats, mine haul trucks, excavators), Diesel-fueled engines and power drives remain an instinctive choice because there are currently little attractive alternatives without performance trade-offs. Compared to automotive systems, industrial engines have 3 major advantages that support the implementation of alternative drive train concepts.

- Despite low load profiles and high idle times, industrial drive trains accumulate a lot of operating hours and therefore have a very high fuel consumption. Investments in more efficient propulsion solutions can pay of very quick.
- In industrial applications the operators and owners of the heavy machinery are used to provide the refueling infrastructure by themselves. Operators do not need to wait for political decisions or other companies to provide any investment in public infrastructure.
- Driveways, work cycles and ambient conditions are at least semi predictable. This enables to tailor innovative power train solutions to specific applications for an optimum ratio of operational cost savings versus initial investment.

1.1 Mobile fleet operations

In industrial applications fleet operations are very common. In harbors multiple tug boats are pushing or pulling the same large container vessel. In mining a fleet of dump trucks is working in a team with large excavators for earth moving. In oil and gas several pump units join to pump water for well stimulation purposes.

While in some applications direct load sharing with energy transfer between units is feasible in others the main goal is intelligent orchestration of machinery to distribute work between several units to achieve a common performance.

1.2 Fleet topology of initial application

For well stimulation a fleet of 12 to 20 pump units is accompanied by a sand supply unit, a sand-water blending unit, an acid mixing unit and other power generating units, each one carrying its own diesel engine.

Fig. 1.1 illustrates a typical pump unit, which consists of a 1.678 kW Diesel engine C (Caterpillar 3512 C) connected to a 7-gear transmission D (Caterpillar TH55-E70) that drives a quintuplex plunger pump E (FMC WQ2700).

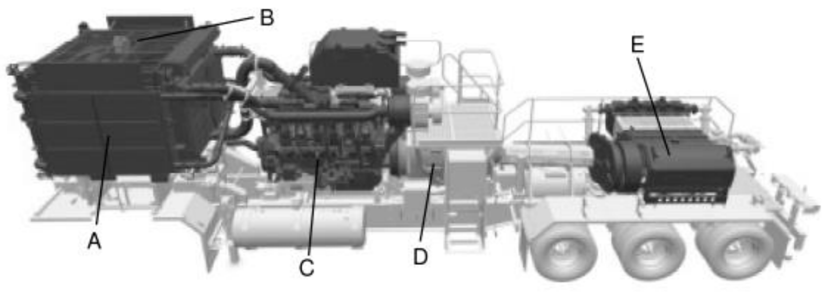

Fig. 1.1: Setup of a pump unit [1]

1.3 Recurrent operation procedures

The process of pressure pumping lasts approximately 2 hours per stage. Before each stage the well is prepared for pumping operation. Generally, this takes up to 1.5 hours. If the process or logistics are interrupted, the non-operating time can last up to a few days. During all this non-operating time the engines of all fleet members are on idle. Fuel consumption of the pump unit engine with all hydraulic auxiliaries (for fan and power end lubrication pump) applied is up to 14 gal/hour. Of the 12 installed units with a total capacity of 20 MW propulsion power in average only 9-10 units are used to deliver the required pumping power. Fig. 1.2 shows the number of working units during a well stimulation process.

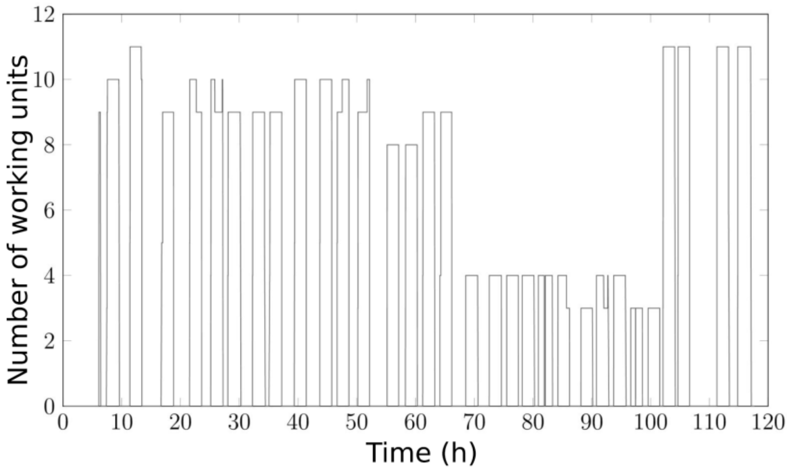

Fig. 1.2: number of working units during well stimulation process [1]

Pump units have a very high usage with up to 4.500 operating hours per year, but due to overall process economics 40% to 60 % are idle time, which economically is unused investment of fuel and material wear.

2 Electrification of Equipment

EKU Power Drives (EKU) develops hybrid industrial power technology at the leading edge of clean energy, electric motor technology, industrial battery assembly and management, industrial internet of things (digitized, intelligent, interconnected industrial equipment), and compliance with increasingly stringent regulation (both environmental and industry specific).

2.1 ESC - Engine Standby Controller

EKU has developed a stand-alone power module (Fig. 2.1) based on Lithium-Ion battery cells that replaces traditional lead-acid batteries of heavy-duty machinery. The power module has been designed to deliver up to 4.000 A peak power to electrically start various engines in a power range of 500 – 3.000 kW and in different mobile industrial applications. Integral part of the power module is the Engine Standby Controller. The modular controller design features various multi-purpose inputs and outputs and communication interfaces to J1939 and Ethernet networks. The application software and the Battery Management System (BMS) is integrated into the control unit. A set of 24 programmable overload-protected high side switches enable enhanced monitoring and controlling of the power outputs.

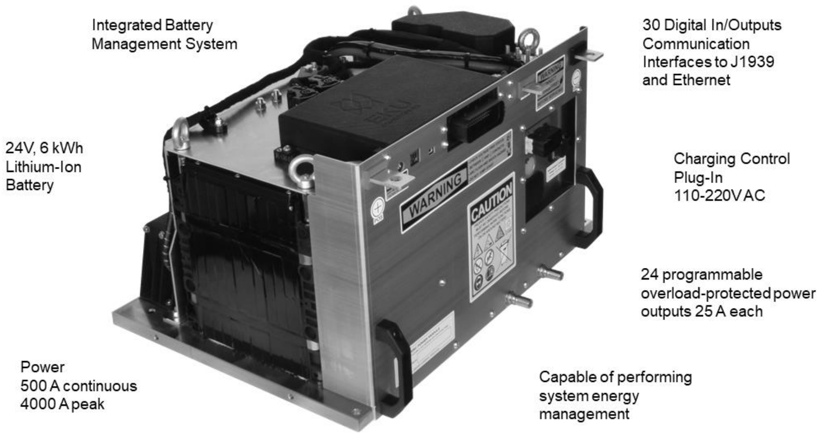

Fig. 2.1: Power Module of Engine Standby Controller

EKU integrates the ESC system in the pump units shown in 1.2 replacing the hydraulic starting system that relies on an external power source (e.g. Tractor trailer engine). The lithium ion battery sources power for the application energy management. The embedded software in the ESC controllers takes over the powertrain availability responsibility. The operator/user is not required to monitor the powertrain and can focus on the application. A typical EKU user today manages up to 20 powertrains simultaneously, and each ESC manages the powertrain independently, assuring load operation at any time. In the pump unit example, when the operator sets the transmission into break, the ESC automatically stops the engine instead of idling. The powertrain transitions to the standby state and can restart at any time with the operator’s pump power request. During the standby phase, the user is concentrated on the application. The ESC system ensures immediate powertrain availability by maintaining the operation temperature and continuous lubrication on the powertrain. Furthermore, the ESC system monitors the battery energy, to assure enough electric power to restart operation. In case that the powertrain is exiting the OEM specifications to operate at full load, or the available battery energy is running low, the ESC system automatically restarts the engine and restores the required temperature and battery charge quickly. When the ESC system reaches the standby required values, it automatically shuts down the engine and the powertrain transitions back again into standby state. The integrated automation software enables the pump unit to be fully available at all time.

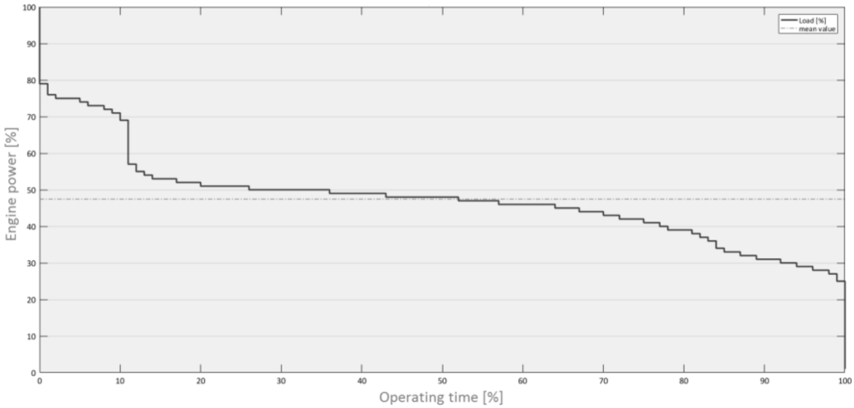

Fig. 2.2: Load Factor of pump unit with ESC

With an ESC system installed, the amount of engine idle time can be reduced up to 98% and due to the reduced non-load operation, the engine load factor increases from 24% to 49%. Fig. 2.2 shows the load factor after 800 operating hours of a pump unit with ESC system installed.

Additionally, the ESC includes the required hardware for creating IOT (Internet of Things) interfaces. Industrial application usually lacks on the required interfaces for IOT implementations.

2.2 Mild Hybrid with bi-directional power

The concept for the next step of electrification is the enhancement of the pump unit to a mild hybrid. Therefore, all hydraulically driven auxiliaries are powered by electric motors. The necessary power is generated from the engine’s power take offs. Fig 2.3 shows the available excess power during the well stimulation process.

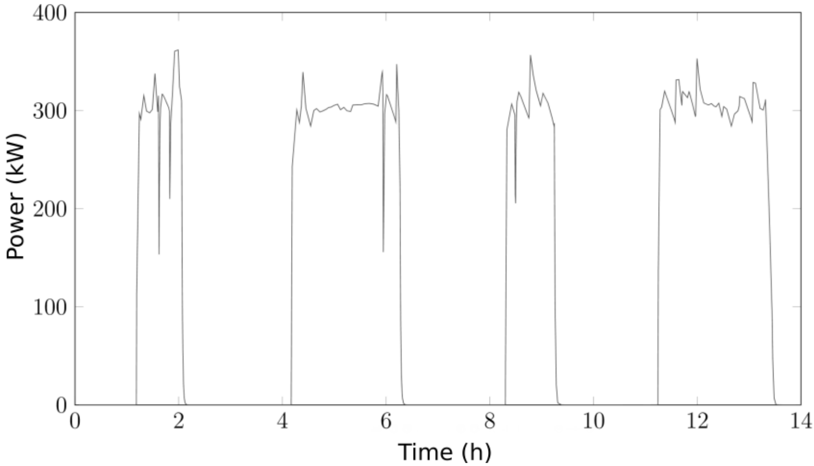

Fig. 2.3: Residual engine power during well stimulation process [1]

The generated power is stored in an additional Lithium-Ion Battery with a nominal voltage of 466 VDC. The mean residual engine power is divided to power the radiator fan (Fig. 1.1 B), the lube pump of the power-end (Fig. 1.1 E) and external systems connected to the micro grid. The nominal on-board link voltage of the pump unit is 1.000 VDC.

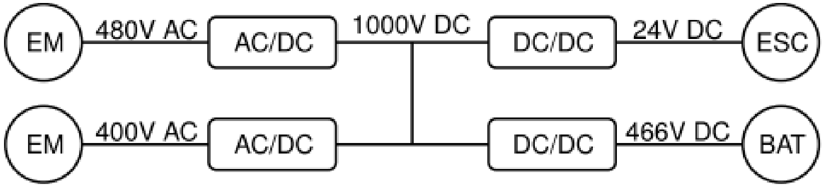

Fig. 2.4: Schematic setup of the pump unit board grid [1]

The mild hybrid pump units of the array are connected on the link voltage level to form a local microgrid that enables power transfers between them. The high link voltage of 1.000 V helps to reduce currents and cable diameters between the grid members. In a mobile application it is crucial to take into account the weight and practicability of cable and connector handling as the system has to be reconfigured very often and in short time.

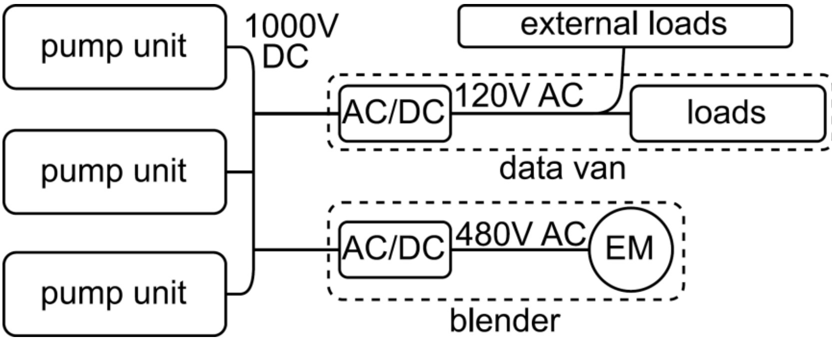

Fig. 2.5: Schematic setup of the fleet micro grid [1]

3 Energy Management in distributed Systems

The distributed system of this presentation is designed for the power management of mobile industrial fleet applications without creation of a single point of failure. The mobile systems operate a technical process and can be removed or added during operation. The main goal is to increase the efficiency of the entire industrial fleet without creating considerable weaknesses in its reliability.

The distributed system allows to dynamically share load between units of the fleet. Furthermore, it allows to use surplus energy to supply an islanded microgrid and thus operate indirectly connected systems, such as tools and command trucks in the fleet. To be able to determine the requirements of the network, attention must be paid to the distributed control system. Various control system designs were examined regarding the required network traffic, network interconnection and needed computing power.

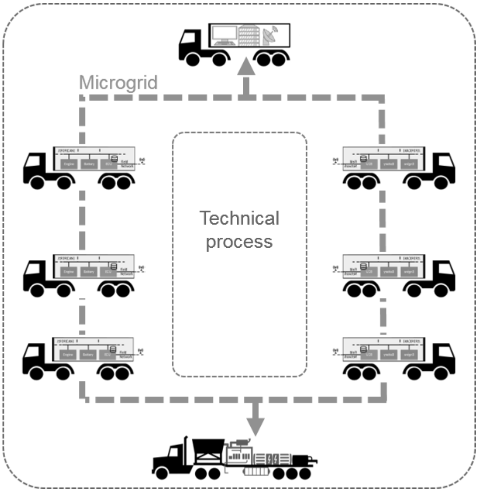

Fig. 3.1: Mobile industrial fleet connected to an islanded microgrid [2]

The local power grid is supplied by pump units (Fig. 3.1) which are locally distributed in a ring of 12 to 20 pump units. The units are placed approx. 2.5 m apart from each other and directly connected by short link cables to build the local power grid. Operating this islanded microgrid without a single point of failure requires that the individual units control the global average voltage and dynamically share the load of the power grid without a centralized control system. The load of the microgrid must be shared dependent on the current position and the power capacity of the individual units, while there is no exact information about losses on the power transmission lines and the positions of the loads. As this is a mobile application, the network topology changes frequently.

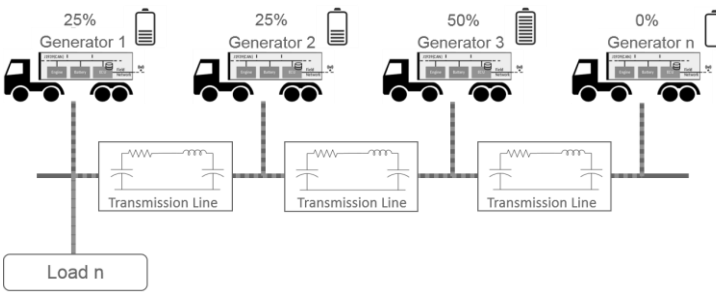

Fig. 3.2: Load sharing in microgrid applications [2]

In the fleet topology of the initial application, all units are equipped with the power modules of the ESC-Engine Standby Controller and power electronics for the connection to a DC-Microgrid like shown in (Fig. 2.1) and (Fig2.4).

The Power Module of the ESC-Engine Standby Controller is based on an embedded system and provides the necessary connectivity and computing power for the operation of the distributed system. The Engine Standby Controller communicates with the subsystems of the pump unit using the internal j1939 CAN-Network. The communication in the fleet is based on an industrial ethernet network.

A cooperative control algorithm for multi-agent systems [7] was designed for the initial application. Compared to alternatives like model predictive controllers it allows a global transient response in a distributed control system while executing classic control algorithms on the single units. No optimization algorithm must be calculated, and processing power can be saved on the embedded system.

The global transient response can be calculated with the resulting Laplacian matrix from the directed communication graph of the system. It represents the interconnection of the communication in the distributed system.

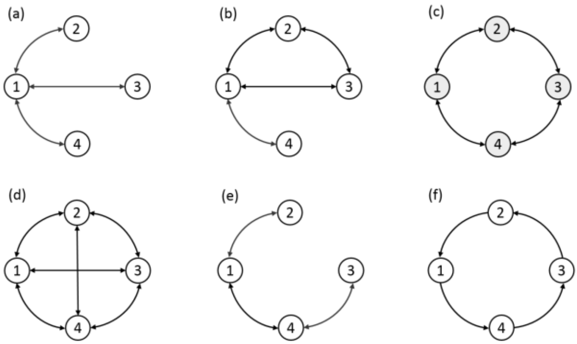

Fig. 3.3: Interconnection examples of the possible directed communication graphs

The cooperative control algorithm is a solution for the tracking synchronization problem of coupled dynamical systems, where all agents are required to act as one group towards one synchronization goal [7]. This control design ensures a stable control loop even when communication failures occur between the units. It is also possible to remove or add units during operation. However, the settling time of the global transient response will be affected by changes in the interconnection of the directed communication graph. This must be considered in the design of further control systems for low-inertia microgrids.

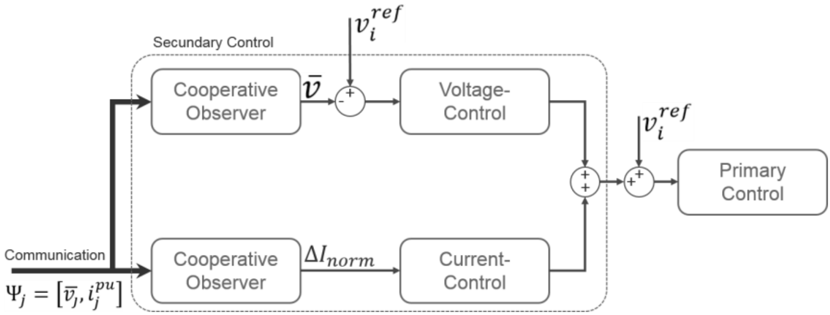

Fig. 3.4: Cooperative control system on the units of the mobile industrial fleet

The control system on every unit consists of a primary and secondary control loop. The primary control loop operates the power electronics output based on the reference v_i^{ref} and the target voltage Δv_i. The target voltage Δv_i is calculated by the secondary control loop. It consists of a voltage and a current control loop. The target values $\bar{v}$ and ΔI_{norm} are calculated by observers based on the dynamic consensus algorithm of multi-agent systems. The observers need every unit to communicate their estimated global average voltage and normalized current value $\Psi_j = [\bar{v}_j, i_j^{pu}]$ periodically. By processing the estimations of the other units, the observer updates its own estimations. As long as the network remains in the minimum spanning tree, all observers will converge to each other.

4 Data Distribution

The design of a reliable, adaptive distributed system requires a communication middleware for dynamically scalable networks without a Single-Point-Of-Failure. The Data Distribution Service is an Open-Standard middleware Specification by the Object Management Group [6] which combines a high scalability with the performance needed for real-time communication systems. It is based on the Real-Time Publish/Subscribe Protocol – RTPS from the Real-Time Industrial Ethernet Suite IEC-PAS-62030 and combines other protocols for a data-centric design of the communication network [5].

A list of vendors is published by the object management group with implementations of the specification for variety of target hardware and software applications. Considering the target hardware some aspects of the DDS-Specification are not implemented or replaced by proprietary concepts in the different vendor-specific implementations, thus making them sometimes incompatible. There are, however, vendors that are working together for a better interoperability of their implementations. For the initial application and simulation of the discussed distributed systems just some functions of the Real-

Time Publish/Subscribe Protocol are necessarily needed for the evaluation of the concept.

Fig. 4.1 shows the different entities of the Real-Time Publish/Subscribe Protocol and how they are associated to each other.

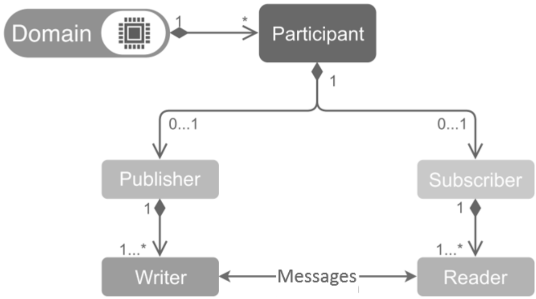

Fig. 4.1: Data Distribution Service communication entities of the specification [4]

RTPS describes the physical network node as a **Domain** with logical network **Participants**. A Participant consists of one or more **Publisher** or **Subscriber** processes. Each Publisher and Subscriber shares meta-data about each other via IP multicast packets. This is done through data **Reader** and **Writer** processes, following the RTPS network protocol. The meta-data includes Topic and QoS-Information (Quality of Service) of the Publisher and Subscriber. **Topics** are unique data structures which specify the name and data types of the shared information. Quality-of-Service policies are used to get control and visibility into the communication behavior, including data throughput, timing and resource utilization.

The communication between Publisher and Subscriber entities is established automatically if the Topic and QoS information matches. Fig. 4.2 shows an exemplary logical network design based on the data distribution service specification.

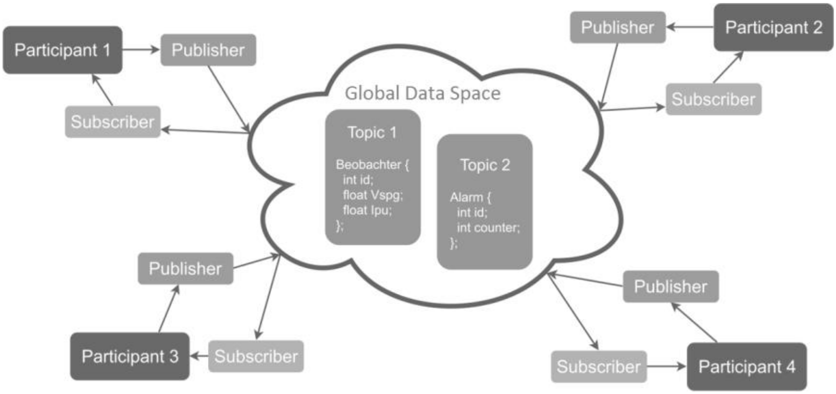

Fig. 4.2: Network design based on the data distribution service specification

Every Participant corresponds to one pump unit of the fleet. In the initial application each Participant is represented by one Publisher and Subscriber with the two Topics Observer and Alarm. The connection is established automatically by the DDS Standard when the shared Topic and QoS-Policy information matches. The Application software with the implemented control algorithm will be informed by callback functions if a new matching Publisher is found. The voltage and current observer of the application software will automatically start to calculate their estimations according to the additional data.

5 Data management

For the overall goal of optimizing the efficiency of the mobile factory, data management is a key factor to success. While the ESC system is making its contribution in a local context on each machine and the mild hybrid allows real-time cooperation by sharing power between multiple machines in the field, the next consequent step towards smart usage of resources is the combination of live and previously recorded data in a global orchestration of the machinery.

Under the project name 'Sophia', EKU is currently developing a data management solution for monitoring and strategy planning that works together closely with the ESC system and Mild Hybrid network, but also allows integration of third-party devices and applications.

Sophia is a hybrid cloud system, combining local interconnection of edge-computing devices, embedded in the control system of each machine, with a global internet- or company intranet connected service back-end. This architecture allows to benefit from inter-machine communication not only using internet connectivity, but also in isolated stand-alone networks on remote temporary factory or construction sites, while on the other hand managing data in a globally synchronized infrastructure.

To accomplish a gapless monitoring of the machine's states and activity, a 'digital twin' of its components is hosted on the embedded computer system. This allows to keep track on all events and system data relevant to the determination of system condition, wear level and key performance indicators, as well as providing information about the machine's capabilities and current restrictions to other systems in the network. Based on this information, distributed cooperative control systems can make automated decisions to optimize the overall system efficiency and wearout.

While the 'digital twins' of all machines primarily 'live' on the embedded computers, they are asynchronously sending their current state to the global cloud back-end and receive operational parameters that influence their processes and interaction to follow a global fleet strategy, such as optimization towards maximum productivity or more towards energy-efficiency or minimized wearout.

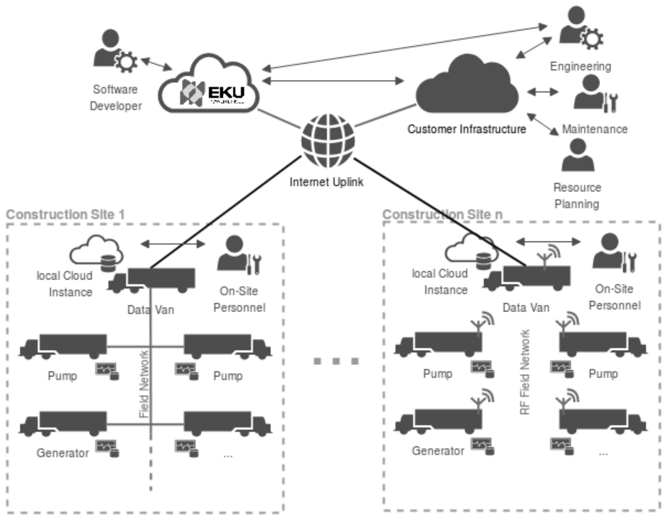

Fig. 5.1: Sophia Cloud Topology [3]

As the data management solution allows a deep insight into the fleet's current condition, it will help maintenance mangers to plan repairs and overhauls, give feedback of the overall fleet performance to the managing directors and allows machine learning algorithms to transfer system knowledge from one system to another, therefore increasing the benefits with the number of similar units managed by the system.

The Sophia system will further support customers by implementing common open standards, such as the XML-based WITSML and open REST APIs to interface with approved industry-specific software. The open, loosely coupled system architecture allows fast integration of additional interfaces for today's fast changing requirements on data processing.

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