No 727481 RESERVE

D3.6 v1.0

Report on Requirements on scalable ICT to implement Voltage Control Concepts, V1

The research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 727481.

Project Name	RESERVE
Contractual Delivery Date:	30. 09. 2018
Actual Delivery Date:	29. 09. 2018
Contributors:	EDD, WIT, UPB, RWTH, UCD
Workpackage:	WP3
Security:	PU
Nature:	R
Version:	1.0
Total number of pages:	29

Abstract:

This document is a report on the Information and Communications Technology Requirements for RESERVE. This document provides a summary of these requirements, as relevant for Voltage Control concepts discussed in work package 3. The requirements are based on the scenarios identified in D3.1 for future 100% RES penetration. For frequency control, D2.4 has specified the ICT requirements on detailed level in RESERVE.

Keyword list:

Information and Communications Technology Requirements, 100% RES Energy Networks, Voltage Control Concepts

Executive Summary

This deliverable reports on the ICT aspects and requirements for the various methods of voltage control in the RESERVE project. It is the first version of this document, labelled D3.6. A later and final second version of this deliverable will be labelled D3.7.

This Deliverable (D) 3.6 presents the work of Task (T) 3.6, “Requirement on scalable ICT to implement voltage control concepts” within the wider context of Work Package (WP) 3 and RESERVE. This task covers the investigation of the ICT requirements of the new concepts for voltage control and relates them to the capabilities of 5G-based ICT systems. WP3 addresses Voltage Stability by Design.

The ongoing transition from conventional power generation, typically based on coal- and gas-driven plants, to renewable energy sources with a share of up to 100% is a major challenge especially for transmission and distribution system operators. They will need predictable power reserves in order to provide a reliable voltage management service. The current technologies for wind turbines and photovoltaic power generation do not ensure sufficient power reserves for voltage control, and do not secure the necessary level of voltage stability.

The first ICT requirements for Voltage Control have already been presented in Deliverable D1.3. This document will now update and analyse the particular requirements for selected scenarios in Voltage Control.

Note the following deliverables in RESERVE will discuss further detailed aspects of ICT requirements for future energy systems, and suggest some solutions:

D2.5 Definitions of ICT Requirements for Frequency Control, V2

D3.7 Report on Requirements on Scalable ICT to implement Voltage Control Concepts, V2

Advanced ICT concepts are needed to monitor and to control the network, by continuously collecting measurements from all parts of the network, and by quickly responding to any disturbances in the grid.

This deliverable includes an overview of the major stakeholders, the selected scenarios and their options in Chapter 2. This chapter 2 also includes updated descriptions of the relevant concepts to be investigated by this project, as they are relevant for the ICT requirements.

On a detailed level, Chapter 3 presents each selected scenario on an individual and more detailed level, followed by a summary of the relevant ICT requirements for each variant. The ICT requirements are finally summarised in a table view in Chapter 4.

A stable voltage level is essential to prevent smart grids from disturbances or even outages. This deliverable shows that some scenarios have demanding requirements for high-performance, reliable, secure, and fast communications networks, to ensure that the voltage control algorithms can swiftly respond to any deviations in the grid. The number of energy generation units will grow drastically, and with it the number of end-points and control units in the network. Consequently, it is highly recommended to deploy future mobile networks for this challenging task, providing effective and cost-efficient solutions for the requirements discussed in this publication.

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1 Introduction

Renewables in a Stable Electric Grid (RESERVE) is a three-year project funded by the European Commission in the Work Programme Horizon 2020 – Competitive Low-Carbon Energy (LCE) 2016-2017. The project officially started in October 2016.

1.1 Task 3.6

This deliverable is the most relevant output of Task 3.6 in WP3. This task collects and analyses the high-level capabilities of 5G-based ICT systems for voltage control. This analysis will lead to secure, resilient and scalable mechanisms for voltage control solutions for low and medium voltage distribution systems. The focus is on transmitting wide-area field measurements and control commands for these mechanisms. This report will also provide an overview of communications and energy architectures that are relevant to the lab and field trials to be executed in test beds of WP5.

1.2 Objectives of the Work Report in this Deliverable

- To provide a systematic analysis of the energy scenarios relevant to the simulations and field trials for voltage control from the ICT perspective;
- To provide the basis for future experimentation in RESERVE using simulation with communications systems as hardware in the loop;
- To provide the basis for investigating the potential role of new 5G-based ICT systems in supporting new management techniques in the power infrastructure;
- To establish a basis for providing input to 5G standardisation processes in relation to the requirements of the stakeholders as we move towards 100% RES;
- To contribute to the preparation of field trials in RESERVE;
- To provide the basis for investigating solutions necessary to the ICT requirements of the power sector in the 100% RES context;
- To investigate the most relevant data interfaces and coding implications of existing network codes in RESERVE on frequency as a basis for work on defining potential modifications to existing codes.

1.3 Outline of the Deliverable

The present deliverable covers the revised version of the information and communications technology requirements specification for selected scenarios of the Voltage Control domain. It was mainly defined by gathering relevant input from the ongoing research in work package WP3, Voltage Stability by Design. The present document will describe these selected scenarios developed by the project and present the ICT requirements for these scenarios, see Chapter 3 below.

1.4 How to Read this Document

This document can be read independently, but to learn about the details of the scenarios from the electrical point of view, the authors suggest reading deliverables D3.2, D3.3, and D3.5 in parallel.

The following documents cover both approaches for voltage control where indicated:

a) Dynamic Voltage Stability Monitoring (Sv_A; A)

b) Active Voltage Management (Sv_B; B)

Overall, this deliverable (D3.6) is related to the following documents from the RESERVE project:

- D1.3 ICT Requirements
- D3.1 Power Electronics Stability Criteria for AC Three Phase Systems (A, B)
- D3.2 Demand Response and DG control considering Voltage Control and Stability
- D3.3 Power Electronics System-level stability criteria
- D3.4 Network Impedance Characterisation for Active distribution Networks
- D3.5 Specification for an on-line system level monitoring system

The following Figure 1-1 summarises the workflow in Work Package 3, and the related input and output between related tasks and deliverables.

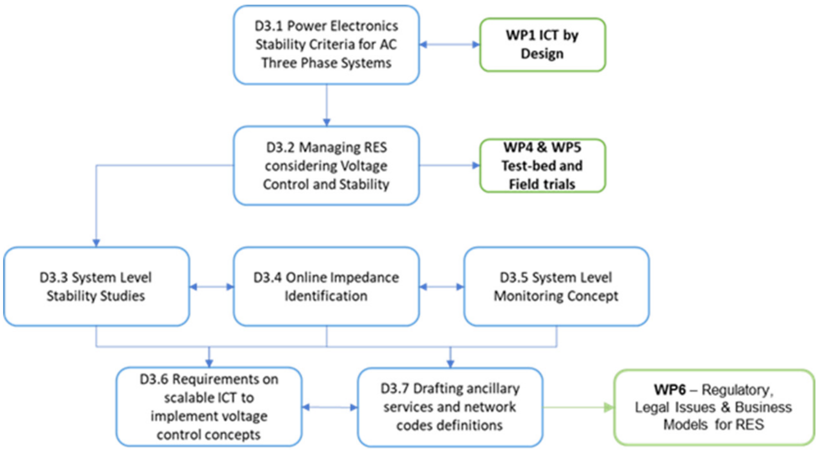


Figure 1-1: Relations between Deliverables in WP3 and other Work Packages

1.5 Approach Used to Undertake the Work

The following steps were iteratively applied to develop the results reported in this deliverable:

- A detailed investigation of the key scenarios selected in Work Package 3 was performed with the partners active in WP3 in the project.
- A categorisation of the options for the architecture of the scenarios was developed and used later as a basis for the ICT requirements definition.
- A categorisation of the ICT potential requirements was developed as the basis for the systematic analysis of the detailed energy scenarios.
- Conclusions regarding the key ICT requirements were developed. These requirements relate to the domains of voltage and frequency control respectively.
- In addition to requirements, this document will also show some relevant ICT solutions for the requirements described.

2 Selected Scenarios and their Options

The technical and commercial aspects of power networks are evolving rapidly. New services, new technologies, new stakeholders, and new business models are emerging, and the industry will face continuous evolution of these aspects in the coming years.

2.1 Sector Actors in Future Energy Networks

The following paragraphs give a short description of the most prominent sector actors in Energy Networks for the next ten years.

Transmission System Operator (TSO): a legal actor responsible for operating, maintaining, and developing the transmission system in a country or a certain region of the country. The TSO is responsible for trading power with the neighbour countries. The Grid Code [4] is the technical document which establishes the rules governing the operation, maintenance and development of the transmission system and sets out the procedures for governing the actions of all transmission system users. International cooperation between TSOs is defined in minimum requirements by the EU, in a guideline on electricity transmission system operation [5].

The TSO will need an ICT system which is reliable and allows for effective communications with connected DSOs as well as neighbouring TSOs in other markets. Typically, the number of communication points in a transmission network is significantly lower compared to distribution grids. Consequently, both 5G networks and powerline communications can provide adequate solutions for the operations of the TSO.

Distribution System Operator (DSO): a legal actor responsible for operating, maintaining, and developing the distribution systems in a given area, and its connections with other systems. The DSO aims to balance reasonable demand and supply of energy, and thus maintain a stable grid. The Distribution Code [3] describes the technical aspects of the relationships between the DSO and all other users of the distribution system.

The DSO will provide connectivity and support for a high number of distributed energy resources in its smart grid. Typically, the communication points in a distribution network may include inverters, substations, and other points, and their number can reach 1,000 to 100,000 devices depending on the size of the smart grid. For this reason, 5G mobile networks provide future-proof and economic solutions to connect such a vast number of devices for reliable and performant data transmission.

Virtual Power Plant (VPP): VPP is a system that integrates several types of power sources, such as wind turbines, small hydro, photovoltaics, back-up generator sets, and batteries, so as to give a reliable overall power supply. The sources are often a cluster of distributed generation systems, which are typically orchestrated by a central authority.

Aggregator: the commercial aggregator (CA) receives forecasts for demand and distributed energy sources (DERs), regarding the load area which it has been assigned to. Forecasts for generation and demand are available at the CA data exchange platform. The CA formulates the offers for flexibility services and energy production/consumption for its load areas, and then sends the offers to the market operator. Consequently, after receiving the schedules for the DERs, once the market clearing and validation phases have been completed, the CA forward the schedules to the corresponding DERs.

Prosumer: traditionally, the roles of energy consumers and suppliers were clearly separated. With the advent of renewable energy generation, that is no longer the case. An increasing number of private and commercial consumers are also operating photo-voltaic generation equipment, and wind turbines whose energy will be injected into the local smart grid.

Microgrids: they comprise Low-Voltage (LV) distribution systems with DERs (microturbines, fuel cells, photovoltaics (PV), etc.), storage devices (flywheels, batteries), energy storage systems, and flexible loads. Such systems can be operated in both non-autonomous way (if interconnected to the grid) or in an autonomous way (if disconnected from the main grid).

2.2 Voltage Control Scenarios

A highly critical application of grid stabilisation deals with voltage control. This application is performed in different time frames, with different network components and architectures, and with two different approaches labelled Dynamic Voltage Stability Monitoring (Sv_A; A) and Active Voltage Management (Sv_B; B)

2.2.1 Time Scales in Voltage Control

The time limits in the following sections are approximated, and the aim is to reduce these time frames in the mid-term future.

Active Voltage Management is a concept which can be deployed in the near-term future, and requires less disruptive changes to the distribution grid. Dynamic Voltage Stability Monitoring, is an approach which provides a more advanced and predictive solution, but also needs new hardware in the form of WSI tools in the system.

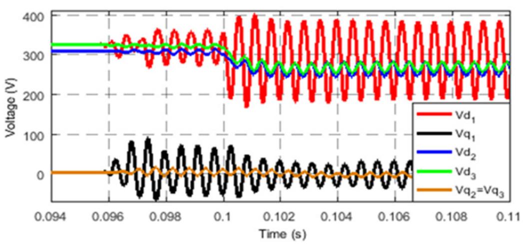
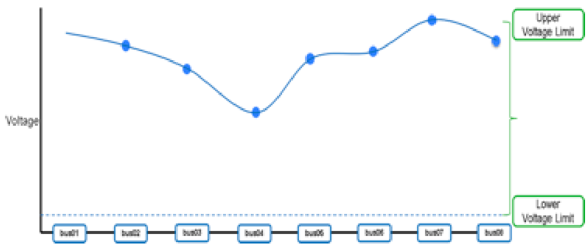
2.2.2 Two voltage control scenarios in RESERVE: Sv_A and Sv_B

This project investigates two different voltage control scenarios which are compared on a high-level in the following sections.

Sv_A addresses dynamic voltage instabilities which may arise from the high number of power converters in future distribution systems. The focus of this scenario is on monitoring impedances and deriving the changes of the voltage in the near future. Based on this, the scenario will control the risk of voltage changes in the distribution grid.

Sv_B aims to maintain the voltages in the distribution network in their allowed limits, minimising any power losses and voltage unbalances in the system. The focus of this scenario is on stabilising the present, current voltage levels, this scheme has the same objective as existing voltage control mechanisms.

Table 2-1: Overview of Scenarios in Voltage Control

Dynamic Voltage Stability Monitoring Sv_A	Active Voltage Management Sv_B
	
Investigation of the voltage-transient voltage harmonics and stability Implementation of Virtual Output Impedance (VOI) control	High number of controllable power converters
Focus on future dynamics of voltage levels	**Steady-state** voltage control High number of controllable power converters

Note that this project will not execute any simulation comparing both approaches, ie Dynamic Voltage Management (Sv_A) versus Active Voltage Management (Sv_B), the reason is that their respective objectives are different.

2.2.2.1 Sv_A – Dynamic Voltage Stability Monitoring

In Dynamic Voltage Stability Monitoring, RESERVE proposes the use of Virtual Output Impedance (VOI) control. VOI control will maintain the dynamic voltage stability in future power systems. The present voltage control does not address dynamic voltage stability. The reason is that dynamic voltage stability is not a concern in today's power systems. However, it will be a concern in future distribution networks due to the connection of numerous power converters. Without dynamic voltage stability, the sinusoidal shape of the voltage will be distorted.

This approach addresses the dynamics of voltage in a LV or MV feeder, that is the rate of change in voltage levels are continuously monitored and controlled, and the focus is on the rate of change, that is the first derivative of the voltage curve in mathematical terms. If the first derivative is 0, then the voltage curve does not experience any rate of change. Compared to Sv_B, Sv_A is more preventive or proactive.

Nevertheless, the Dynamic Voltage Stability Monitoring is also concerned with the absolute values of voltage though, overall this approach is more complex and comprehensive than the more static voltage management of Sv_B.

2.2.2.2 Sv_B – Active Voltage Management

The second scenario for voltage control is Active Voltage Management. This scheme has the same objective as present voltage control approaches. However, instead of using additional power system components such as On-Load Changers (OLTC) or shunt capacitors, the proposed concept will use the electronic power converters available at the customer premises. With this scheme, DSOs avoid additional investments to maintain the root-mean square (RMS) values of the voltage within acceptable limits.

Dynamic voltage stability is not the only concern in distribution networks with distributed RES and ESSs. Present voltage management systems are also likely to fail in the presence of RES penetration levels as envisioned in the RESERVE project. Present voltage control systems do not facilitate a voltage drop anticipated with 100% RES nor do they allow for the possible constraint breaches due to the volt-rise effects of generation on distribution systems.

In static Active Voltage Management (Sv_B), the voltage in all nodes of a the grid, is always maintained in a particular range, otherwise there is a significant risk for a dangerous drop in voltage, or an increase by oversupplying energy from PV solar power generation. This approach puts the focus on snapshots on current points in time, and not on the prediction of future development. Voltage levels are managed by monitoring active and reactive power (P and Q), while regulating the grid with reactive power (Q).

2.3 Applicable Standards

The IEC 61850 suite of standards defines applicable protocols for intelligent electronic devices at electrical substations. [6] It is a part of the International Electrotechnical Commission's (IEC) Technical Committee 57 reference architecture for electric power systems. The abstract data models defined in IEC 61850 can be mapped to some protocols. Current mappings in the standard are to MMS (Manufacturing Message Specification), GOOSE (Generic Object Oriented Substation Event), SMV (Sampled Measured Values), and soon to Web Services. These protocols can run over TCP/IP networks or substation LANs using high-speed switched Ethernet to obtain the necessary response times below four milliseconds for protective relaying.

For this project, the standard in part 7-420 is of particular interest, it addresses communication networks and systems for power utility automation, titled “7-420: Basic communication structure - Distributed energy resources logical nodes”. [7]

3 Scenarios and ICT Requirements

This chapter describes the scenarios so that the resulting ICT requirements can be presented in more detail. In voltage control, each scenario has various alternatives, which are listed and described as well.

3.1 Scenarios for Active Voltage Management (UCD)

3.1.1 General Concepts of Active Voltage Management (UCD)

The active voltage management (AVM) techniques are used to increase the ability of the distribution network to accommodate RES and improve voltage control in distribution networks.

The basic concept of AVM is utilising the reactive power capability of RES to support the voltage profile in distribution networks and maintaining the prescribed relationship to the target voltage.

The traditional AVM implementation requires a centralised command centre which receives measurements from renewable energy sources, and after processing them, it will send a command to each RES. However, the investments required to deploy such omniscient centralised voltage control solutions are substantial, and proving this approach by way of field-trials is unfortunately unrealistic.

Decentralisation

The deployment of the AVM technique of SV_B is achievable in a *decentral environment*. This preferable (and feasible) alternative connects individual renewable energy sources on a case-by-case basis. Until the point in time that the voltage of every node in distribution systems can be communicated, or even estimated within satisfactory accuracy and tolerance, a decentralised approach should be taken. The proposed AVM technique underpins the fundamental prerequisites for deploying such a decentral approach in the future distribution networks.

The successful AVM implementation guarantees the optimal operation of the distribution network and maximises the utilisation of existing infrastructures. This alleviates the need for investing in new assets.

The decentralized active voltage management has been realized by applying **Volt-Var Curves** (VVCs) to obtain the reactive power support that each inverter should provide to achieve a specific objective. A brief summary of the proposed method for obtaining the VVCs is discussed here.

Accuracy of the input data and measurements is of utmost importance and a key factor in extracting a proper Volt-Var control scheme for a low-voltage distribution system enabled with inverter-interfaced RESs and also in developing an effective voltage control strategy in each possible future scenario in such system.

The input data required for extracting the VVCs through the offline simulations are listed below. Figure 3-1: Data required in offline simulations for extracting the VVCs summarizes this list.

- Network characteristics.
    - Network configuration (the three-phase diagram)
    - Line characteristics
    - Fixed reactive power compensators
- Load characteristics.
    - The historical load levels and load model parameters (ZIP coefficients) at each load point.
- Characteristics of the system inverters.
    - Maximum capacity of the inverters
    - Inverter type, connection type (star or delta).
    - Historical data on the energy generation of RESs.
    - Inverter mode of operation (Power control mode or voltage control mode)

- Operator Objectives such as minimization of voltage deviation from a desirable value, minimization of voltage unbalance, minimization of active power losses and so on.
- Inverter impedance as a function of frequency (viewed at the connection point of each inverter).

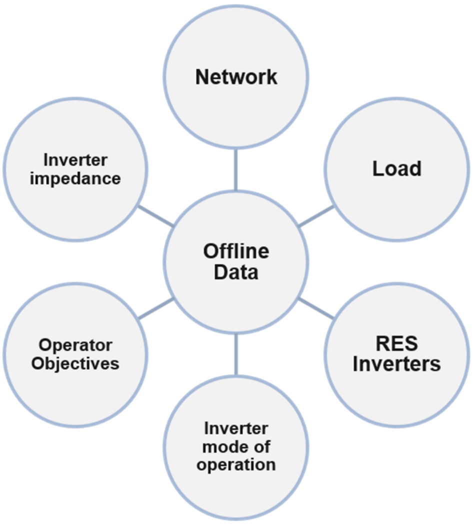


Figure 3-1: Data required in offline simulations for extracting the VVCs

The data required in order to develop the voltage strategies using the VVCs in online application (implementation of the proposed voltage management technique) are listed below. Figure 3-2 summarizes this list.

- Voltage at inverter connection point
- Active and reactive power injection of the inverters before developing the voltage control strategy.
- Additional limitations of the inverters, such as maximum power angle (regarding minimum permissible power factor).
- Network impedance viewed by the inverter from the connection point.

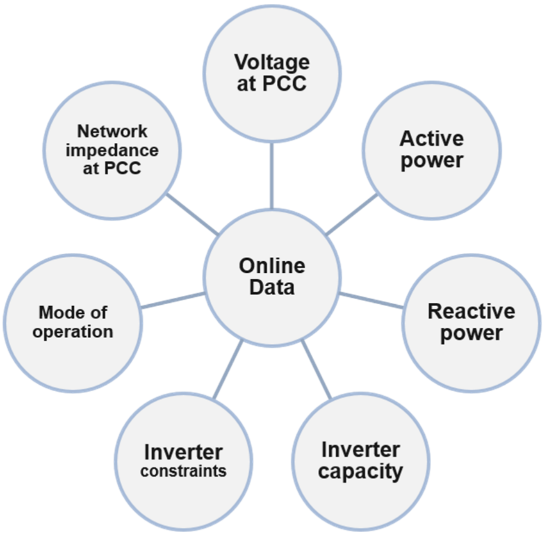


Figure 3-2: Data required for online application of the proposed AVM

The method of obtaining the Volt-Var Curves is outlined below. See Figure 3-3: Summary of the proposed method for extracting the decentralized voltage management scheme for each inverter (proposed algorithm to extract VVCs), the picture summarizes the proposed algorithm for finding the VVCs.

1. Using the historical data on the power production of the renewable energy sources, load levels at different load points and coefficients of the ZIP load model, different scenarios are generated for extracting a VVC for each inverter, which can be used for decentralized active voltage management in low voltage distribution systems. Each scenario include the load level at each load point on each bus, active power generation of each inverter, load power factor and load ZIP characteristics.
2. The optimal value of the change in reactive power support if each inverter unit *i* is then found for each scenario *s* neglecting the limitations on the inverter capacities (ΔQ_{is}).
3. A power flow algorithm is run to find 3-phase voltages for each scenario without applying the reactive power support found in the previous step. To find the voltage level at the connecting point of each inverter (V_{is}).
4. The pair of voltage level and change in reactive support for each scenario and each inverter is found (V_{is} - ΔQ_{is}).
5. For each inverter *i*, apply linear regression to find the VVC that best describes the relationship between V_i and ΔQ_i.

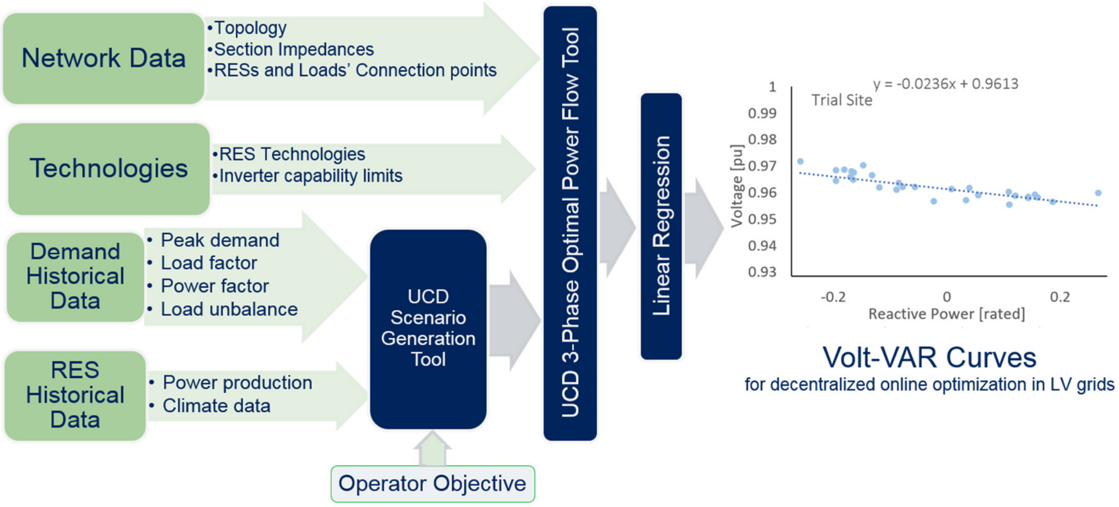


Figure 3-3: Summary of the proposed method for extracting the decentralized voltage management scheme for each inverter (proposed algorithm to extract VVCs)

After extracting the proper decentralized control scheme, ie, VVCs, these VVCs are used to find the reactive power support that each inverter should provide. Application of the VVCs for voltage management across the network is straightforward. It is necessary to measure some local parameters and transfer the measured values to the local control system, in order to develop the proper control strategy.

The voltage at the connection point of each power controller is measured and the measured value is transferred to the local control unit. It is necessary to send the P/Q values of this inverter, since the value of the change in the reactive power support which is proposed by the *respective* VVC may *not* be applicable due to the limited capacity of the inverter or other constraints. In other words: Q (value of reactive power) changes, but the new value change is not possible because the inverter can't handle it, or for different reasons. More details on these reasons can be found in D3.3.

After receiving the required data, each local control unit determines the applicable change in the reactive power injection of regarding inverter and returns the new value of Q. The new reactive set-point of this inverter is transferred to the inverter to change the reactive power support accordingly. Figure 3-4 summarizes this procedure. It should be noted that in a decentralized control system, it is assumed that the local control agent has no information about the other controllable devices installed at other connection points. Therefore, for each inverter, there is a separate local control system.

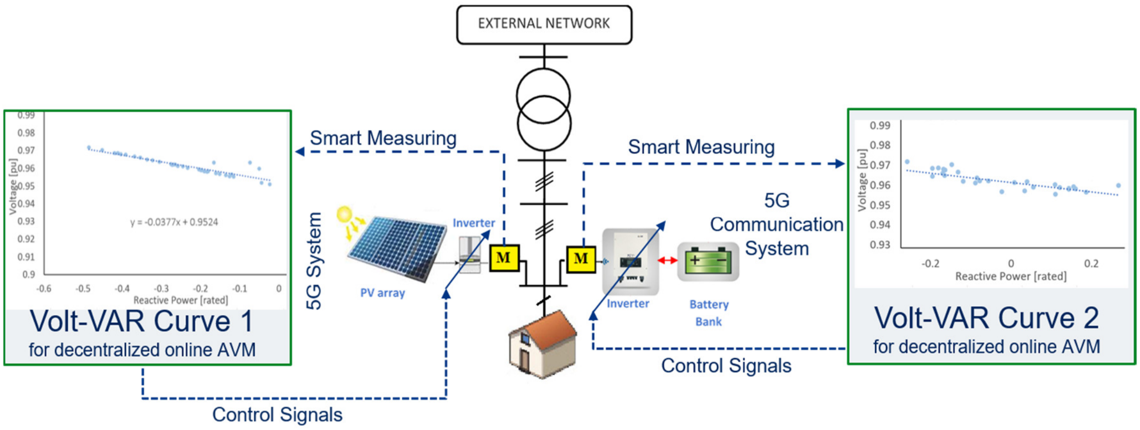


Figure 3-4: Summary of the online application of VVCs for a simple low voltage distribution system with two single-phase inverter

3.1.2 Volt-Var Curve Execution (WIT)

The execution of the AVM algorithm, and more accurately, the Volt-Var Curve (VVC), which is the actionable output from the algorithm, involves an investigation of a set of suitable architectures or approaches. From an ICT perspective, this will allow an effective execution in both a simulation environment, and in trial site implementations.

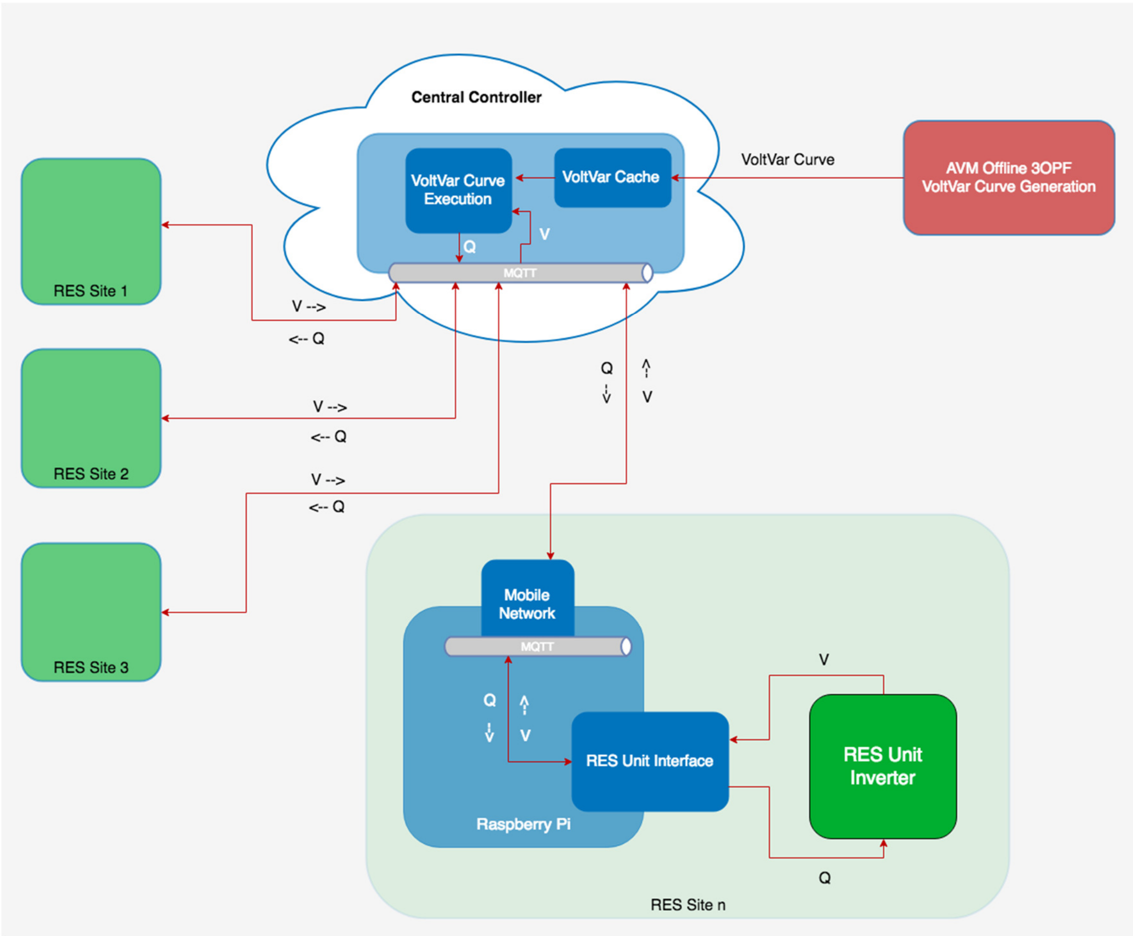
With reference to deliverable D1.3 section 2.3 the author refers to centralised, decentralised and distributed approaches from an electrical engineering perspective. In order to fully explore the potential execution of the AVM, it is important to discuss these architectures in terms of information technology, from a distributed systems approach. This approach has its foundation in communications and networking, and comprises of the interconnection of heterogeneous physical and virtual components distributed across a LAN or WAN for the purpose of data transfer and system control.

The following sub-sections will detail three architectures identified, a **Centralised** model, a **Decentralised** model and a **Hybrid-Edge Computing** model, from the perspective of their mechanics, topological structure and high-level ICT requirements The main differences between each architecture are in terms of the geographical distance between the execution of the VVC and the inverter, and the autonomy of each RES unit from a central control point in terms of voltage management and the granularity of control.

3.1.2.1 Centralised Volt-Var Curve Execution

The diagram in Figure 3-5 illustrates the topology and data flow of a centralised model of the execution of the AVM technique. In this case the Volt-VAR curves for the trial sites would be stored on the cloud server at a central geographical control centre with reference to their specific device or location. The execution will take place on a voltage value contained in the payloads sent from the target site via an MQTT broker running on a mobile network connection with the output of this being the sending of a Reactive Power (Q) set point to the target RES site. This approach has a focus on the communications based focus as the readings are sent to the cloud implementation for processing. This approach requires full time communication and reliance on a central control centre with potential large geographical distance between the target inverter and the execution of the VVC. These geographical distances and the potential to have a large number of devices under one central control point may have impact on the following ICT criteria.

Implementing the AVM with a centralised approach will have a high level of latency. This is due to the messages having to travel long distances between Central Controller and RES Unit. The high frequency of communications from multiple sites can play a factor into the response time too. This will also mean that a high level of information reliability is needed, as many RES devices are dependent on this central server. More computing resources will be required to implement techniques to handle the large number of messages and to ensure none are lost. The data volume would be of medium level, because while the message itself is small, there is overhead involved, such as authentication and encryption. Communication will occur over public networks, which means messages will require high levels of security, because if this centralised system is compromised it can have a severe impact. The data sent and received has to be confidential and trustworthy. MQTT allows for messages to be encrypted with no significant loss in performance.



The MQTT broker will also require authentication in order to send/receive messages.

Figure 3-5: Centralised AVM Execution Architecture

3.1.2.2 Decentralised Volt-Var Curve Execution

The diagram in Figure 3-6 illustrates the topology and data flow of a decentralised model of the execution of the AVM technique. While being managed by the central controller, its only communication is to receive the VVC for execution either on the Raspberry Pi device or for direct input into a smart inverter that would have the native capability and interface to process the VVC. This approach adds a layer of autonomy from central control due to the fact that while the RES site has the VVC it is capable of running independently. The only other communication required would be for an update to the VVC algorithm for a specific RES Unit. From a central cloud perspective, while the VVC execution is being carried on the edge, the physical distance between the inverter and the VVC execution has a lesser impact from a latency perspective, but the potential number of managed objects (RES Units) would remain the same highlighting a potential scalability issue in this approach. Given that, there is an extra layer of computing on the hardware at the RES Site, which is the potential updating of a VVC at each RES Unit. The mapping and sending of a VVC to the correct RES unit is executed at the cloud controller level. The impact of the above requirements, from an ICT perspective, can be evaluated under the following criteria.

A decentralised approach involves having a Raspberry Pi to enable communication between the cloud service and inverter, perform calculations if needed or to simply upload the VVC to the inverter. Implementing this approach will ensure the smallest level of latency due to the VVC being as close as possible to the RES Unit. Frequency of communication is rather low, as each Raspberry Pi is in contact with only one RES Unit at any time, so the demand on computing resources is minimal. However, a decentralised approach will require a Raspberry Pi to be manually installed at every RES Unit that does not have an inverter with mechanisms to receive and process the VVC natively. Information reliability can be kept low as only one RES unit will be affected if the Raspberry Pi is down. The data volume for communication between Raspberry Pi and inverter will be low, the message content will remain the same and the overhead will be minimal as this communication will occur over a direct ethernet connection. The data volume between Raspberry Pi and cloud server will be at a medium level as these messages are sent over public networks where more overhead is required. This public communication is needed to update the VVC, but the frequency of this will be very low. As this will happen over a public network, secure MQTT communication will be needed. A medium level of security would be required, because one RES device can seriously affect the power supply in the local area. The communication to cloud server needs to be secured, but the edge device itself will need to be protected also. This is to prevent any tampering with the edge device hardware and to protect it from various weather conditions.

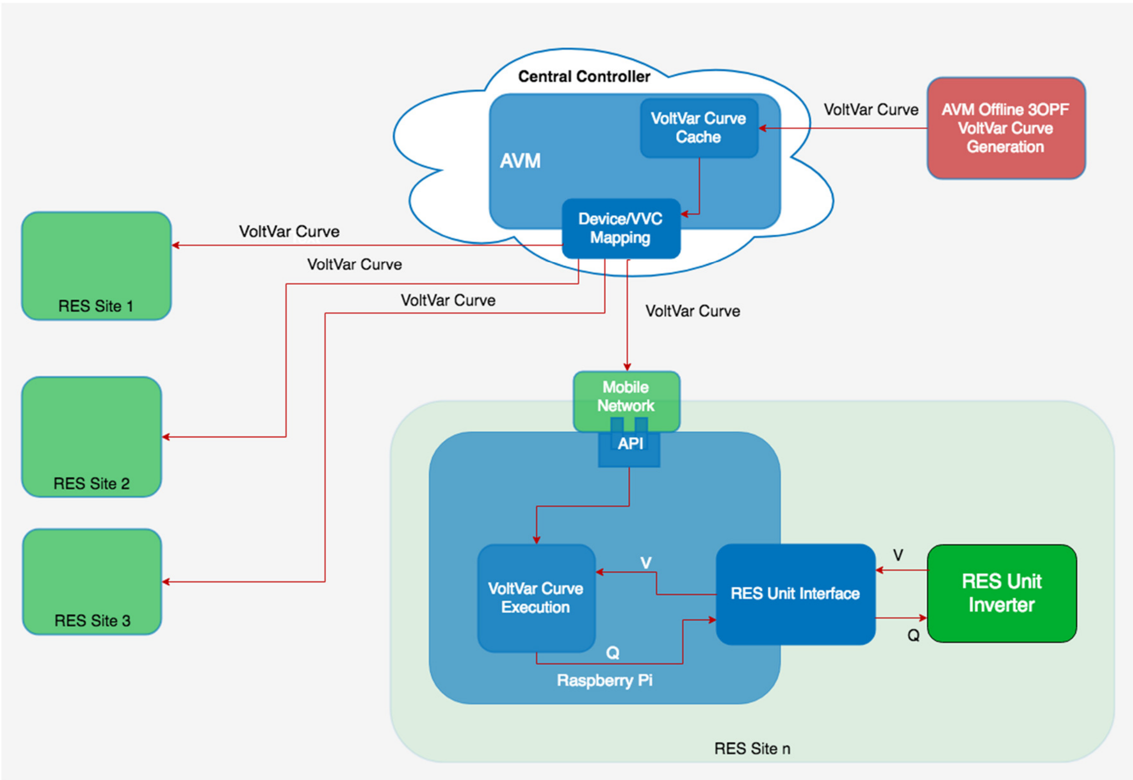


Figure 3-6: Decentralised AVM Execution Architecture

3.1.2.3 Hybrid Edge Computing Volt-Var Curve Execution

Figure 3-7 illustrates a high-level topological view of a hybrid implementation of the AVM technique using both a centralised and a decentralised approach:

- Centralised approach in terms of the initial creation of the VVC's
- De-centralised approach, or edge-computing application, deployed to regional cell tower entities with computational capabilities to control the orchestration and execution of the VVC's at RES sites in specific regions.

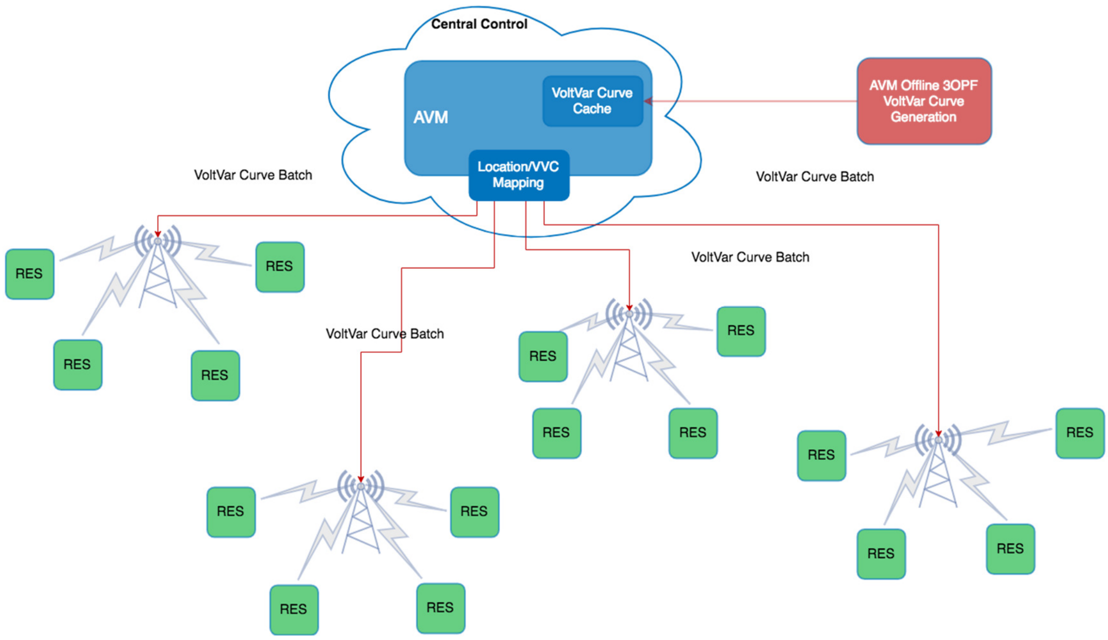


Figure 3-7: AVM Hybrid Approach Architecture

The diagram in Figure 3-8 details the data flow and components required for a hybrid approach at a regional level. The core component is a computing node at the edge of the communications network, co-located with the 5G radio base stations in the access network towers. The computing node has preconfigured knowledge of each distributed energy site in its area, including computational capabilities, connection details and the specific VVC. This site specific configuration can drive the level of computing required for each RES site and carry out the required computation accordingly. From the detail gathered in D5.2 it is clear that there are three levels of computational capabilities. These levels are, the inverter being capable of accepting a VVC, the setpoint calculation can be computed at the RES Unit using the voltage and VVC and

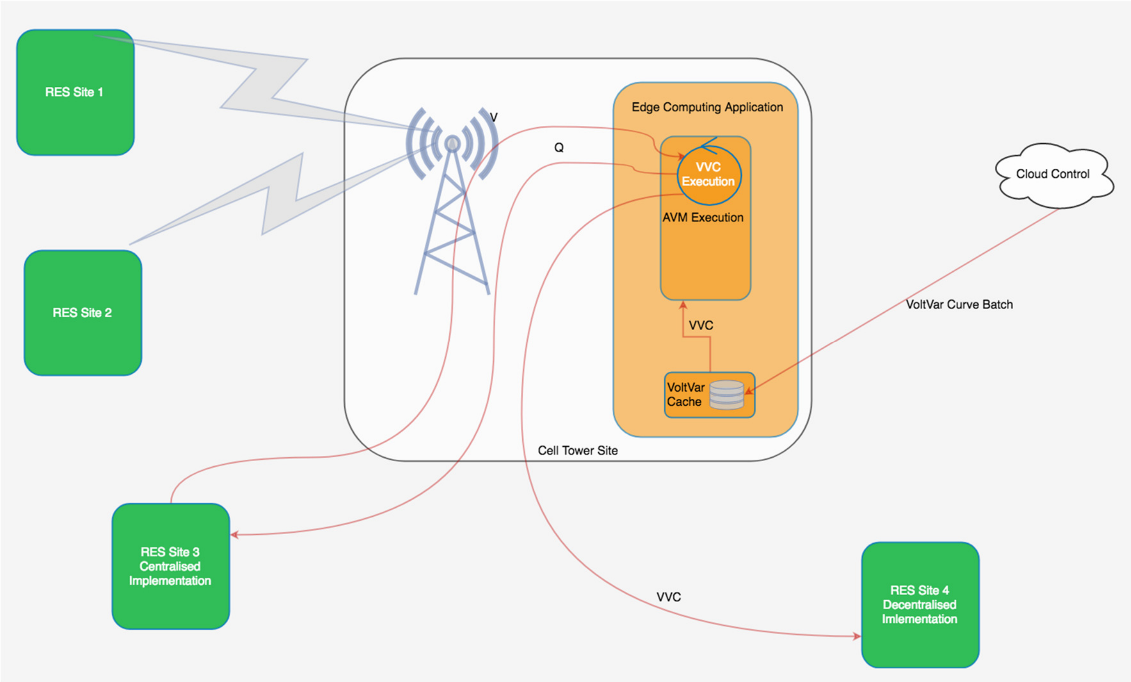


Figure 3-8: AVM Hybrid Approach Regional Implementation

the RES unit is only capable of sending voltage and receiving a setpoint value. To summarise this approach in terms of ICT requirements, we need to evaluate it on the following criteria.

A hybrid approach can be seen to have a medium frequency of communication level, because it will have to manage multiple RES devices from multiple sites, but not on the same scale as a centralised system. The frequency of communication between edge node and cloud server would be rather low, as the server will need to send down multiple VVCs to the device. The latency would be low as there should not be a significant distance between cell tower site and RES site. Medium levels of information reliability are to be expected due to multiple RES Sites being dependant on the edge device. The data volume would be of medium level too, because while the message itself is small, there is overhead involved, such as authentication and encryption. The security level would be medium, it would have a serious impact on the RES devices in the immediate area. All communication is sent over a public network and must be secured. The edge device is more exposed than a centralised server, measures will be needed to prevent damage to the hardware.

3.1.3 Summary of ICT Aspects for Decentralised Active Voltage Management

Table 3-1: ICT Aspects of Active Voltage Management

ICT Aspect	Decentralised Active Voltage Management
Latency per Cycle	2 to 4 seconds Limited number of messages, algorithm is executed on local edge level
Typical Message Size	Up to 100KB (updating the Volt-Var properties)

Acceptable Packet Loss	None (use protocol with retransmissions)
Availability Unplanned downtime	99.99% Below 4.38 minutes per month
Resilience	Incomplete or distorted messages must be checked and re-transmitted
Data Security	Maximum protection against any form of illegal intrusion into the communications system, including reading, changing or deleting data during transmissions or in storage
Privacy	Must meet all applicable national and European regulations

3.2 Scenarios for Dynamic Voltage Stability Monitoring (RWTH)

3.2.1 Introduction to DVSM

This scenario places the focus on the dynamics of voltage in a LV or MV feeder, which is the rate of change in voltage. This change rate needs to be continuously monitored and controlled, that is the first derivative of the voltage curve in mathematical terms. If the first derivative is 0, then the voltage curve does not face any rate of change. In comparison to Sv_B, Sv_A is more preventive and proactive.

The Challenge: when the share of renewable energy sources is getting higher, the risk of oscillations and resonance is growing, leading to instability of voltage levels. Figure 3-9 shows a scenario where this risk is visualised.

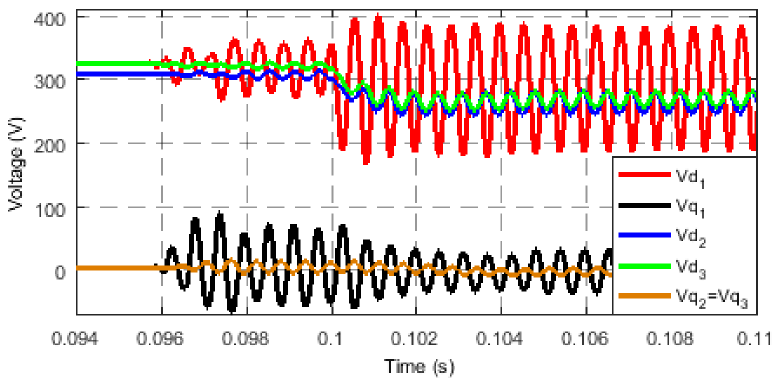


Figure 3-9: Voltage Oscillations and Resonance in an LV Feeder

As Dynamic Voltage Stability Monitoring (DVSM) is also concerned with the absolute voltage values in the grid, his approach is more complex and comprehensive than the Active Voltage Management described above. Figure 3-10 shows the implementation of the Dynamic Voltage Stability Monitoring in a LV feeder setting. The key elements are the secondary substation automation units (SSAU) and the inverters (electronic power converters) connecting the distributed energy sources.

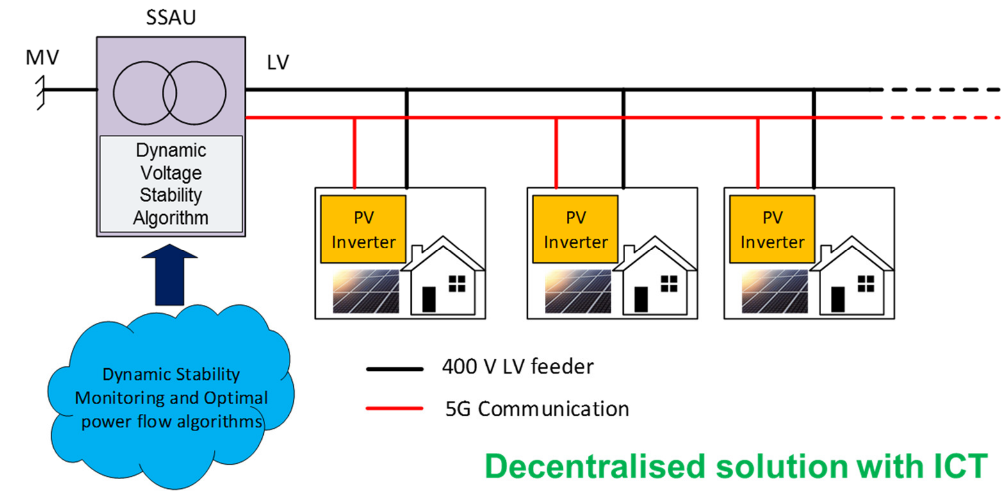


Figure 3-10: Typical Deployment of Decentralised Dynamic Voltage Stability Monitoring

The secondary substation automation unit (SSAU) hosts the voltage stability algorithm as a software component, and this program behaves as a coordinator gathering the information from the inverters to compute stability margins and send back control commands back to the inverters. The SSAU performs the evaluation of stability margins once an hour for each inverter.

The approach in Figure 3-11 is based on the Middlebrook theory (see section 7.3) where the stability can be determined using the **inverter output impedance** and the **grid impedance** as input. See Figure 3-11 below.

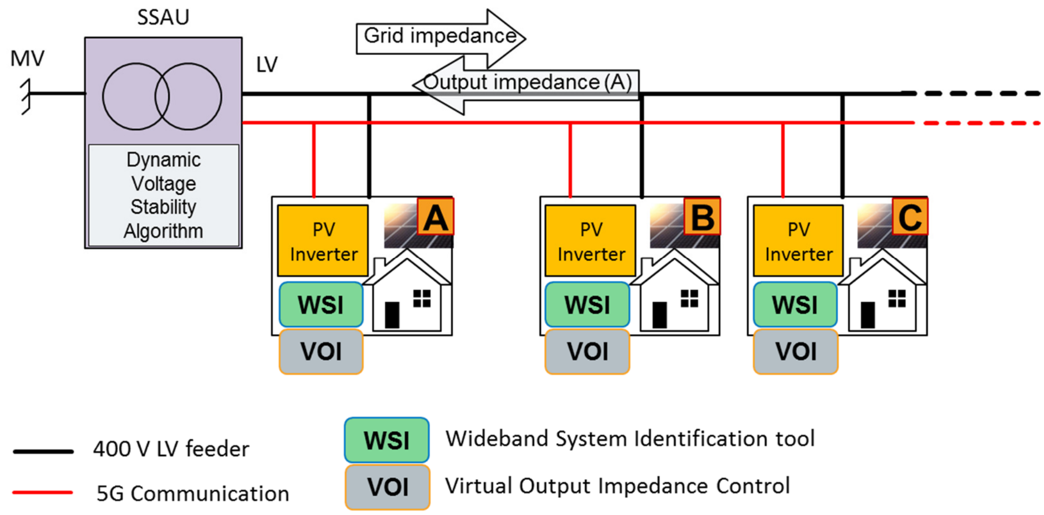


Figure 3-11: Impedance Monitoring and Control

For the measurement of the impedances, a wide-band system identification (WSI) tool is present in the inverter. The WSI tool injects a pseudo-random binary sequence (PRBS) signal into the controller in the inverters and processes the incoming voltage and current measurements to determine the impedance.

In the DVSM technology, the SSAU intends to modify the behaviour of the inverter. For this purpose, the SSAU sends an initiation signal to Inverter A to use its WSI tool to measure the *grid impedance*. The inverter's *output impedance*, on the other hand, is mathematically modelled in the controller of the inverter. The output impedance of the inverter is a function of the physical parameters of the inverter such as power filter parameters and the control parameters. Therefore, at any given point during the operations, the controller of the inverter knows the output impedance of the inverter.

The coefficients of the identified grid and output impedance are sent back to the SSAU. The SSAU performs stability analysis based on the Middlebrook theory, computes the stability margins and, if required, sends back control commands to the virtual output impedance controller (VOI) of the inverter A. This process is repeated for Inverter B and furthermore for all other inverters present under the direct control of the SSAU.

3.2.2 Location of the WSI tool

There are two places where the WSI tool can be placed in the DVSM concept, either locally in the inverters, or centrally in the substations. See also D3.5.

3.2.2.1 WSI Tool Location in RES Inverters

- The controller of the inverter has the complete WSI algorithm. This includes the subroutines like PRBS noise generation, extracting the non-parametric impedance and parametric impedance identification.
- The Inverter uses communication to communicate only the identified impedance coefficients. Communication data volume is low.

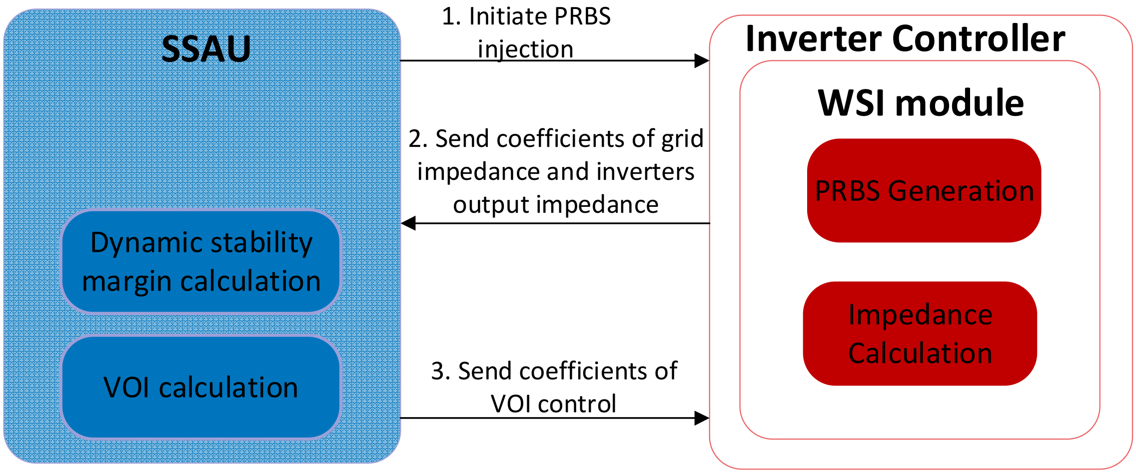


Figure 3-12: System-level Integration of WSI located in Inverter

Considering that the process repeats for an inverter every 5 minutes.

Data Volume/Bandwidth

- Floating point (double precision) – 8 bytes per number
- Number of floating point numbers per inverter (considering VOI coefficients) – 100
- Number of inverters (1 Inverter per end-point) – 500
- Kilobytes per second – 8*100*500/(1024*300) = 1.3021 kBytes/s
- Kilobits per second – 10.41 kbits/s

3.2.2.2 WSI tool Located in SSAU

- The controller of the inverter has only the PRBS noise generation subroutine.
- The rest of the WSI functionalities such as extracting the non-parametric impedance and parametric impedance identification is performed in SSAU.
- The Inverter uses communication to send voltage and current data measured during the perturbation. Communication data volume is high.

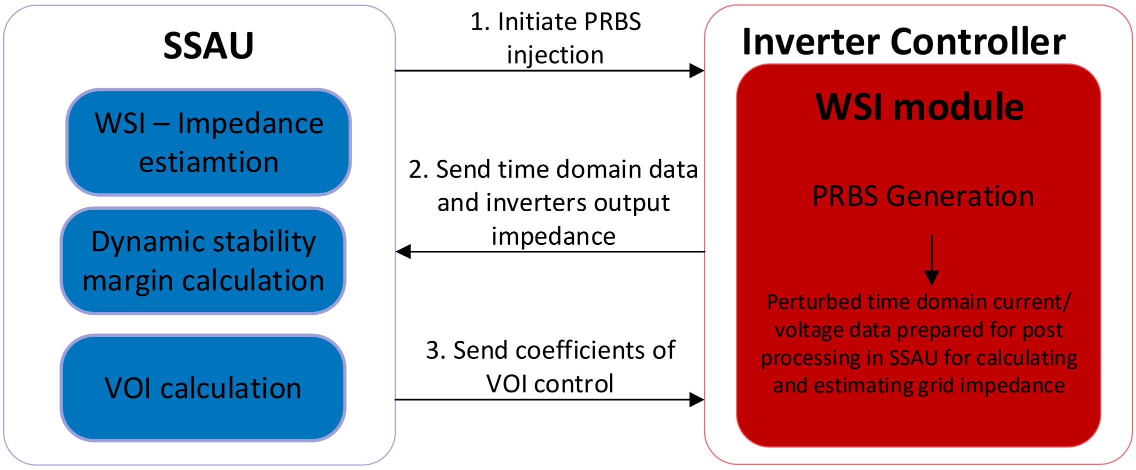


Figure 3-13 System level integration of WSI when implemented in SSAU

Data Volume/Bandwidth

Considering the sampling frequency within the inverter controller of 50 kHz and the number of fundamental cycles (N) of the power system frequency of 50 Hz for which the measurements are recorded, the number of data points can be calculated as: Ns=N*50kHz/50 Hz.

- Floating point (double precision for coefficients) – 8 Bytes per number
- Number of floating point numbers per inverter (considering VOI coefficients) – 50
- Total bytes for all coefficients = 8bytes*50 =400 Bytes
- Time domain data of perturbed signals – 2 Bytes per number
- Number of channels (Vd,Vq,Id,Iq) – 4
- Number of fundamental cycles N -10
- Number of perturbed time domain data - 10*50,000/50 =10,000
- Total bytes of perturbed time domain data – 10,000*4 channels* 2 bytes = 80,000 Bytes
- Overall total data - 80,000 Bytes (from time domain data) + 400 Bytes (Coeffcients) = 80,400 Bytes
- Number of inverters (1 Inverter per end-point) – 500
- Kilobytes per second – 80,400*500/(1024*300) = 130.86 kBytes/s
- Kilobits per second – 1047 kbits/s

3.2.2.3 Impedance Data

Dynamic Voltage Stability Management uses the *impedance* to control voltage levels. This applies to both measurements in the grid as well as to control commands if corrective actions are needed.

It is recommended to perform the impedance monitoring and control only for one inverter at a time, as inserting PRBS noise at many points of the grid may lead to noise overlay or interference.

The *grid impedance* matrix Z_{grid} consists of 4 components: $Z_{grid,DD}$, $Z_{grid,DQ}$, $Z_{grid,QD}$ and $Z_{grid,QQ}$. Each of these four elements consists of 12 coefficients with floating point numbers. For example, $Z_{grid,DD}$ consists of 12 floating point numbers. Therefore, the entire grid impedance matrix is represented by 48 floating point numbers. In this study, the authors round it off to 50 coefficients.

The inverter *output impedance* matrix Z_{out} consists of 4 components: $Z_{out,DD}$, $Z_{out,DQ}$, $Z_{out,QD}$ and $Z_{out,QQ}$. Similarly, there are 50 coefficients for the output impedance.

In the downlink direction, from the substation, the VOI control command coefficients that come from the SSAU contain 50 coefficients too. Note that the VOI control command has the same data format, it is essentially an impedance matrix too.

Therefore, in any cycle, the messages will exchange 50+50+50 (150) floating point numbers. The inverters are processed sequentially, and not concurrently. Therefore it can take between two and four seconds for the process to complete for *one inverter*, and a typical LV feeder may have up to 100 inverters, it can take up to 200-400 seconds until the same inverter is monitored again. For each cycle, 4 messages of approx 150 floating point numbers are exchanged between SSAU and one inverter.

3.2.2.4 ICT Aspects

The following Table 3-2: ICT Aspects of Dynamic Voltage Stability ManagementTable 3-2 summarises the key aspects of the communications and IT systems in use for this approach.

Table 3-2: ICT Aspects of Dynamic Voltage Stability Management

ICT Aspect	Dynamic Voltage Stability Management
Latency per Cycle	2 to 4 seconds
Typical Message Size	400 – 1000 Bytes for 50 floating point numbers plus overhead
Acceptable Packet Loss	None (use protocol with retransmissions)
Availability Unplanned downtime	99.99% Below 4.38 minutes per month
Resilience	Incomplete or distorted messages must be checked and re-transmitted
Data Security	Maximum protection against any form of illegal intrusion into the communications system, including reading, changing or deleting data during transmissions or in storage
Privacy	Must meet all applicable national and European regulations

Note that the detailed impedance measurement data are only recorded and stored for later access in situations of low voltage stability. Otherwise there is no need to store the impedance values in databases.

3.3 Protocols and Technology

For a long time, power systems have used a traditional data communications architecture known as “client – server”. The **client-server architecture** is a centralised architecture where a producer and consumer are involved in the processing of power system data, the server acting as the consumer and the client as a producer of data readings from the power system device.

The **server** houses and provides high-end, computing-intensive services to the client. These services can include application access, storage, file sharing, and access to the server’s raw computing power.

The client - server architecture works when the client device sends data to the server over the network connection, via a specific **protocol**, which is then processed and delivered to the server.

In the power systems world, a number of specific protocols have been used over the years from IEC 60870-5-101 to ModBus and DNP3, all of which are examples of this type of centralised client-server data transfer model.

These protocols have been superseded by the more advanced protocol set for power systems based on **IEC 61850** MMS [manufacturing message specification], GOOSE, and Sampled Values. Included in the IEC 61850 set of standards (see section 7.2), there is a dedicated standard for vendor-agnostic engineering of the configuration of intelligent electronic devices (IED) within an electrical substation automation system, and allows for the communication between each IED. The IEC 61850 protocol mapping profile is shown inbookmark2 Figure 3-14.

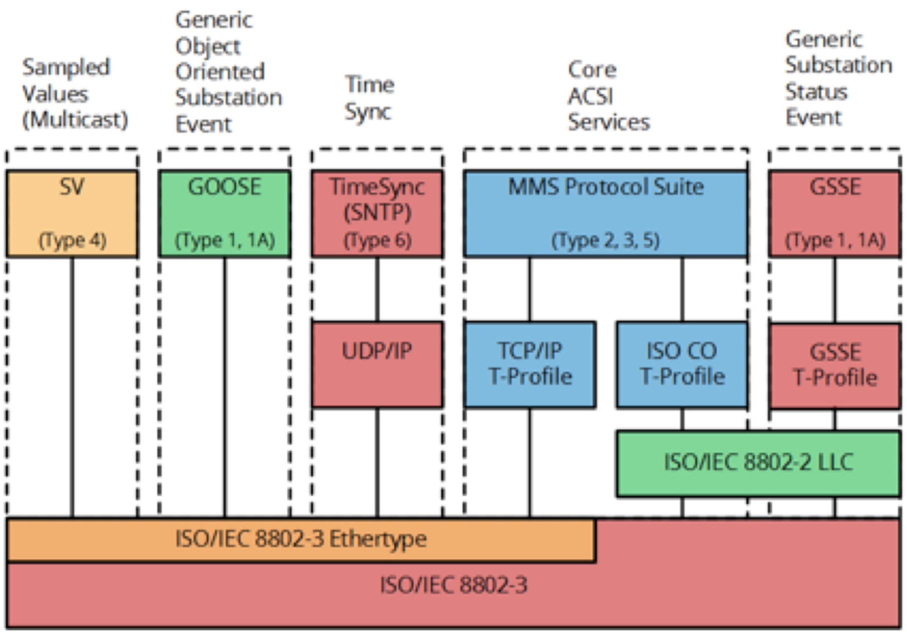


Figure 3-14: IEC 61850 Protocol Mapping Profile

While **MMS** is again based on the client-server architecture there is a multicast option with the Sampled Values (SV), but Sampled Values has one major drawback, it is multicast over the Ethernet networking medium only, which is a problem for modern data communication applications which are distributed across the Internet.

A centralised system is no longer an information communication architecture that can be used to process all of this data, and limits the possibilities of monitoring and controlling the capabilities of new grid systems based on 100% renewable energy.

The way forward is to put in place a distributed data intelligence platform that can support peer-to-peer publish/subscribe messaging using widely available, economical internet technologies. This would mean that power system information no longer needs to go to a central system for decision making. The local data of monitoring/control units in the field can be made available to the power system software computer applications hosted on the distributed cloud.

One such new distributed intelligence platform for power systems is OpenFMB which uses a lightweight Internet of Things (IoT) broker called MQTT (Message Queue Telemetry Transport). MQTT is highly bandwidth efficient and it uses a publish-subscribe model in contrast to MMS / Modbus protocols with their request-response paradigm. Another advantage of OpenFMB is the publish-subscribe model allows for multiple subscribers to register and enrol to consume specific state variables within the messages being published by a IED. Additionally, MQTT supports federation of multiple brokers which thus enables hybrid support for peer-to-peer publish/subscribe messaging.

All in all, this means the DER units in the field can publish their voltage related data to an OpenFMB messaging broker hosted on the distributed cloud, with the voltage control AVM executioner application subscribed to listen for those published messages.

3.4 Summary of ICT Requirements for Voltage Control Concepts

The following Table 3-3 shows the scenarios for voltage control and their ICT requirements.

Table 3-3: Summary of ICT Requirements for Voltage Control

Scenario	Active Voltage Management	Dynamic Voltage Stability Management
Architecture	De-centralised	De-centralised
Time Aspect	Continuous monitoring required, messages should be transmitted as fast as possible	
Communications	Advanced Mobile networks between central control units and local power converters Very large number of remote devices in distribution network	
Connection Points	Future Distribution networks may contain between 100 and 100,000 electronic power converters/inverters, and other end points for monitoring and control. The typical distance between local converters/inverters and control centres is 2 to 500 kms The communication devices, ie 5G modems, must be controlled by an IOT system that provides for easy and swift configuration and orchestration.	
Frequency of Communi-cations	Typically 1 per second	Typically 1 per second
Latency	Low (< 100 ms)	Low (< 100 ms)
Data volume	0.1 to 100 kBytes	0.1 to 100 kBytes
Security	Medium (serious impact)	Medium (serious impact)
Availability of ICT system	High (99.99%)	High (99.99%)

4 Conclusion

This document describes the relationship between the power network architectures being considered by the project for the voltage control scenarios of RESERVE and the ICT architectures and capabilities needed to implement them.

The report describes the differences between the two approaches for voltage control. Compared to frequency control, the two approaches for voltage control are less time-critical and require less bandwidth from the ICT service provider and the mobile network operator. Voltage is regulated only for one LV or MV feeder, not for the entire smart grid of a distribution system operator. So, even the number of connecting points in any of the algorithms discussed is rather limited.

For the DSO’s, the key aspects are maximum availability of the ICT infrastructure and maximum data security. All in all, it can be concluded that the use of 5G mobile networks will be the future-proof solution to support the future concepts for voltage control which may not reach commercial maturity for five years from now.

5 List of Figures

6 List of Tables

7 References

7.1 RESERVE Deliverables

- D1.3 ICT Requirements
- D3.1 Power Electronics Stability Criteria for AC Three Phase Systems (A, B)
- D3.2 Demand Response and DG control considering Voltage Control and Stability
- D3.3 Power Electronics System-level stability criteria
- D3.4 Network Impedance Characterisation for Active distribution Networks
- D3.5 Specification for an on-line system level monitoring system

7.2 IEC Standards

1. IEC 61850, an overview, available online: https://en.wikipedia.org/wiki/IEC_61850
2. IEC 61850-7-420:2009 Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes
3. IEC 61850 - Communication Networks and Systems in Substations: An Overview of Computer Science, Jianqing Zhang and Carl A. Gunter University of Illinois at Urbana-Champaign, available online at http://seclab.illinois.edu/wp-content/uploads/2011/03/iec61850-intro.pdf

7.3 Middlebrook Theory

1. R. D. Middlebrook, “Input filter considerations in design and application of switching regulators,” pp. 366–382, 1976.
2. J. Sun, “Impedance-Based Stability Criterion for Grid-Connected Inverters,” *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3075–3078, 2011.

8 List of Abbreviations

AVM	Active Voltage Management
B2B	Business to Business
CPMS	Charge Point Management System
DER	Distributed Energy Resources
DMS	Distribution Management System (DSO domain)
DSO	Distribution System Operator
DVSM	Dynamic Voltage Stability Monitoring
EAC	Exploitation Activities Coordinator
EMS	Energy Management System (TSO domain)
ESS	Energy Storage Systems
ESO	European Standardisation Organisations
ETSI	European Telecommunications Standards Institute
HV	High Voltage
ICT	Information and Communication Technology
IEC	International Electro-technical Commission
IoT	Internet of Things
KPI	Key Performance Indicator
LV	Low Voltage
M2M	Machine to Machine
MG	Microgrid
MV	Medium Voltage
O&M	Operations and maintenance
PCC	Point of Common Coupling
PV	Photovoltaic (power generation unit)
SCADA	Supervisory Control and Data Acquisition
SME	Small & Medium Enterprise
SS	Secondary Substation
SSAU	Secondary Substation Automation Unit
TSO	Transmission and System Operator
VOI	Virtual Output Impedance
VPN	Virtual Private Network
VPP	Virtual Power Plant
WP	Work Package
WSI	Wideband System Identification