D 5.2 EVALUATION OF CONTROL ALGORITHMS BASED ON LITERATURE AND SIMULATIVE TESTING AND SPECIFICATION OF MOST PROMISING APPROACH

VERSION 1

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13. December 2021

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INTERNAL REFERENCE

Deliverable No.:	D 5.2 (2021)
Deliverable Name:	Evaluation of control algorithms based on literature and simulative testing and specification of most promising approach
Lead Participant:	Oliver Kraft
Work Package No.:	WP5
Task No. & Name:	T5.4
Document (File):	-
Issue (Save) Date:	2022-25-02

DOCUMENT STATUS

	Date	Person(s)	Organisation
Author(s)	2022-25-02	Oliver Kraft	ie3, TU Dortmund
Verification by			
Approval by			
Approval by			

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LIST OF ABBREVIATIONS

Abbreviation	Definition
D	Deliverable
DER	Distributed energy resource
DS	Distribution System
DSO	Distribution System Operator
FO	Flexibility Operator
FOR	Feasible Operation Region
FSM	Flexibility Service Mechanism
GCP	Grid connection point
HV	High voltage
LV	Low voltage
MV	Medium voltage
OPF	Optimal power flow
P	Active Power
Q	Reactive Power
SPC	Smart Power Cell
SWOT	Strength Weakness Opportunities Threats
TS	Transmission System
TSO	Transmission System Operator
WP	Work Package

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1 INTRODUCTION

1.1 Objective

The ERA-Net funded project HONOR – holistic flexibility market integration of cross-sectoral energy sources – covers the development and evaluation of a trans-regional flexibility market mechanism, integrating cross-sectoral energy flexibility at a community-wide level. Deliverable (D) 5.2 aims at providing a review on approaches to provide a requested active (P) and reactive (Q) power flow at the Grid Connection Point (GCP) to an upstream voltage level by controlling the flexible units within the power system.

It is closely connected to D5.1 [1] and to two corresponding publications [2] [3]. In the first part of D5.1 a Flexibility Service Mechanism (FSM) is being developed and subsequently evaluated for relevant use cases in a case study. The second part of D5.2 then addresses the control center integration including visualization concepts and the user interface.

1.2 Scope

The scope of this Deliverable is to evaluate different FSM approaches through a Strength-Weakness-Opportunities-Threats (SWOT) analysis in order to provide a recommendation for the control center integration in WP8. This is being achieved through a literature review of potential control algorithms.

1.3 Approach and structure

In Section 2 the detailed scope is being described in order to establish the necessary target for the subsequent evaluation of various approaches. This is being coupled with a literature review on classified groups for the control algorithms. In Section 3 the evaluation scheme is defined based on various criteria, before it is applied in Section 4 on some control algorithms from Section 2. Based on the evaluation a specification of the most promising approach is given coupled with a simulative evaluation.

2 OVERVIEW ON CONTROL ALGORITHM APPROACHES

In this Section the scope and requirements of the control algorithms within WP5 are defined. Afterwards a literature review on the possible FSM implementations is carried out.

2.1 Technical Scope of Control Algorithms

The HONOR architecture is centred around a local flexibility market for trading between Flexibility Operators (FOs) and the respective System Operator (SO). However asides from the market, where the flexibility from assets is used to support the grid, emergency situation will occur, where the market is not sufficient to mitigate congestion. This is especially the case in real-time situations, where the market is already closed. Also unforeseen events can occur that make subsequent setpoint adjustments necessary to ensure the fulfilment of grid constraints and securing operation. This does not only cover a single grid with one voltage level but can rather be seen as a multi-level process where downstream grids can control units to provide a requested power flow to the upstream grid to mitigate congestion in the upstream grid.

For this purpose the focus of the control algorithms within D5.2 is set on the provision of a requested power flow considering reactive and active power flow at the GCP to an upstream grid, labelled as a FSM. The method thereby focuses on adjustments in the distribution system (DS) to support congestion management in the transmission system (TS). The stated concept results in the demand for solutions considering two elements that will be presented in detail.

2.1.1 Provision of requested P and Q values at the GCP

First the Distribution System Operator (DSO) has to know the range of power flows that can be provided at the GCP in order to communicate this to the Transmission System Operator (TSO). Then the TSO can estimate, which operating points should be achieved for the congestion management at different GCPs. The available power flow range can be estimated and visualized as a two dimensional area considering the active and reactive power. It is defined as the Feasible Operation Region (FOR) and can be seen in Figure 1.

Within the FOR, every point can be seen as a feasible operating point, that can be achieved by controlling the flexible assets in the grid. Hence any valid operating point is within the FOR but can be moved to a different point in the FOR if requested so by the TSO. According to the concept of FSM [2], each of these valid operating points also includes the cost-optimized generation data of the respective generating flexible units.

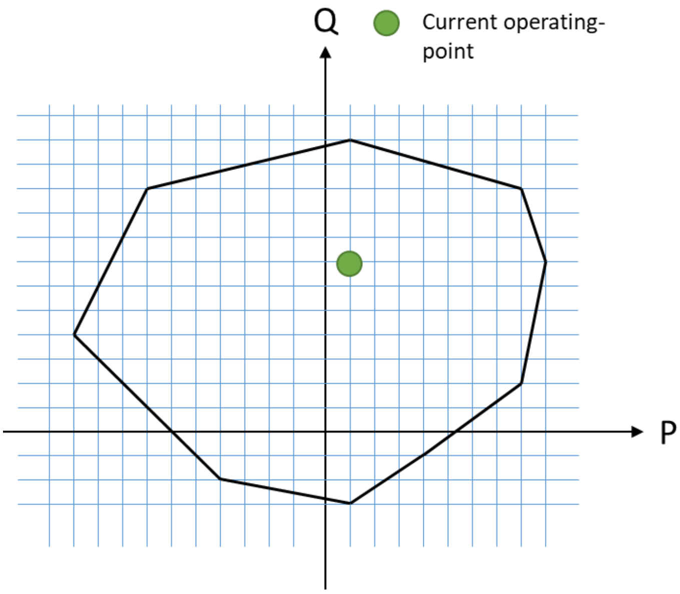

Figure 1: Exemplary FOR with current operating point

2.1.2 Determination of Setpoint Adjustments

The second core element is the setpoint determination of all flexible assets in order to achieve the requested P,Q values at the GCP. Every asset has its own FOR that determines the flexibility potential of that asset. By coordinatively changing the setpoints of many assets, the power flows within the DS are modified to achieve the targeted one at the GCP. This process is visualized in Figure 2.

The FOR of each flexibility asset are being used as one of the constraints to determine optimum flexibility using an Optimal Power Flow (OPF). First of all the network constraints cannot be violated which covers the voltage limits at each bus and the thermal line and

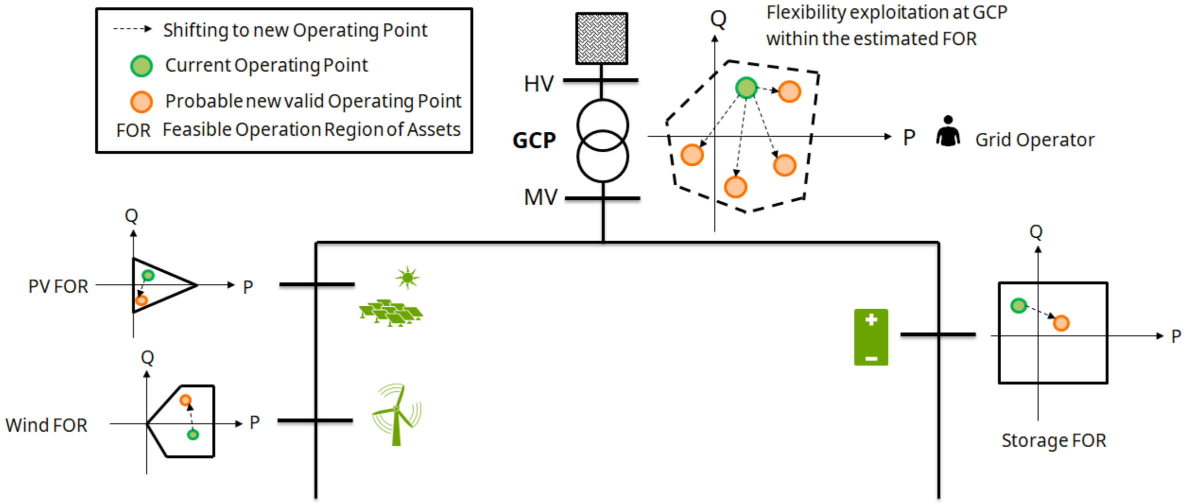

Figure 2: Coordinated setpoint adjustment

transformer capacities. In addition the power flow equations of the system and the FOR limits of each asset through its active and reactive power limits have to be kept. Possible extensions cover the usage of N-1 constraints for power lines.

2.1.3 Correlations and Potential Solving Options

The two mentioned elements from Section 2.1.1 and 2.1.2 are interconnected to some extend which also affects the solving process. As every operating point in the GCP-FOR is achieved through a determined setpoint for each asset, the computation can be combined into one process. This means that for a discrete set of operating points in the PQ-area at the GCP the viability is checked for each point by determining the corresponding unit setpoints which deliver the operating point and do not violate any constraints.

In real-time operation, this is also referenced to the current grid status. Thereby a reference operating point at the GCP describes the current power flow situation in the grid. This point is used to determine the flexibility (or feasibility) with respect to other potential operating points in a cost-optimized approach with the respective constraints using OPFs.

However this does not always have to be the case, as other approaches (for example heuristic or probalistic) can be used to approximate the GCP-FOR independently and to set the unit setpoints (for example by dynamic controllers) in operation. Therefore the following Section introduces various concepts that were identified in literature.

2.2 Computational FSM Approaches

In order to determine the GCP-FOR and the unit setpoints for one operating point at the GCP this Section presents relevant optimization, heuristic, probalistic and dynamic approaches in literature. Two core methods that were identified in this process are optimization approaches, especially as part of an OPF, and Random Sampling (RS) approaches like a monte-carlo simulation [4].

In [5] the authors focus on a time-dependent flexibility estimation at the GCP in a two staged method as seen in Figure 3. The first method uses the RS approach and assumes the availability of all necessary information to the DSO and then randomly generates setpoints for all units, before a power flow determines the feasibility of the generated case. If a case is determined to be feasible, it is accepted to the FOR. After a large number of iterations a convex hull is put around all feasible points and determines the FOR. The second method uses random values to change time series forecasts depending on their uncertainty. Then for each timestep the first method is fully applied to determine the FOR. By overlaying the area for multiple timesteps, a probalistic solution is delivered that consists of a dense area that should be available over the predefined period at a high probability. A similar approach to the second method can be seen in [6].

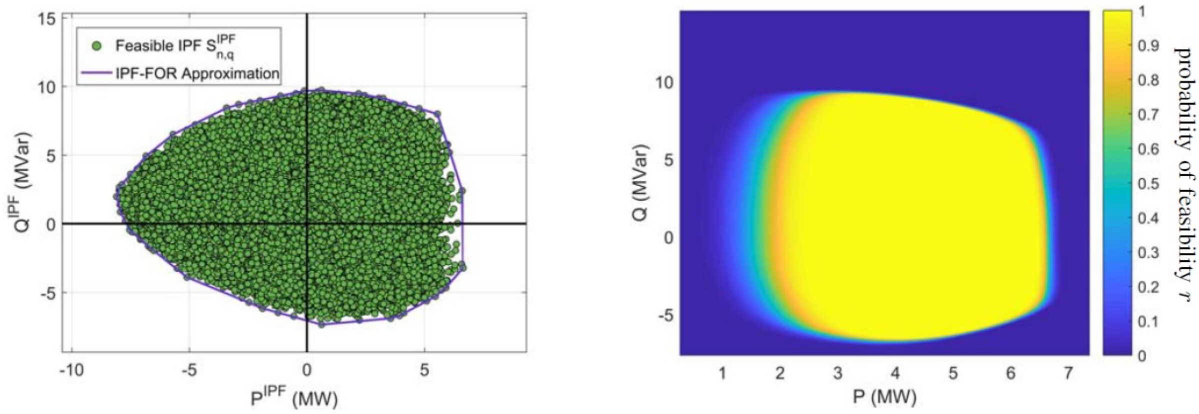

Figure 3: Results from method 1 (left) and method 2 (right) according to [5]

In [7] a dynamic approach is developed considering the provision of an active and reactive power flow at the GCP following a setpoint input by a superimposed control system. The model labels a DS considering of one MV grid with subordinate LV grids as a Smart Power Cell (SPC). In this SPC every flexible asset is equipped with dynamic models and controllers that can react to external signals. However there is no setpoint that gets transferred to the asset. Instead each controller reacts to the targeted P,Q values at the GCP and the currently measured ones by increasing or decreasing the active or reactive power output steadily until the requested power flow is achieved. This is coupled with a monitoring of the nodal voltages which limit the increase or decrease of the flexible assets' output in the feeder if network violations are at risk to be violated. If the requested power flow at the GCP is impossible to achieve within the network restrictions the dynamic system will stop at a feasible point at the border of a FOR, even though the FOR is not estimated separately.

The authors in [8] propose a methodology that uses a set of optimization problems. The novelty of the approach lays in the mapping of costs of the flexibility activations. Instead of just using technical input data and constraints, information of the ownership of assets and the individual pricing is taken into account as well to formulate an interval constrained power flow. The solution delivers a FOR that is internally structured depending on a set of discrete price ranges as displayed in Figure 4. Hence the price ranges radially distribute themselves around the current operating point and every price area is fully surrounded by a price area of a larger price tag.

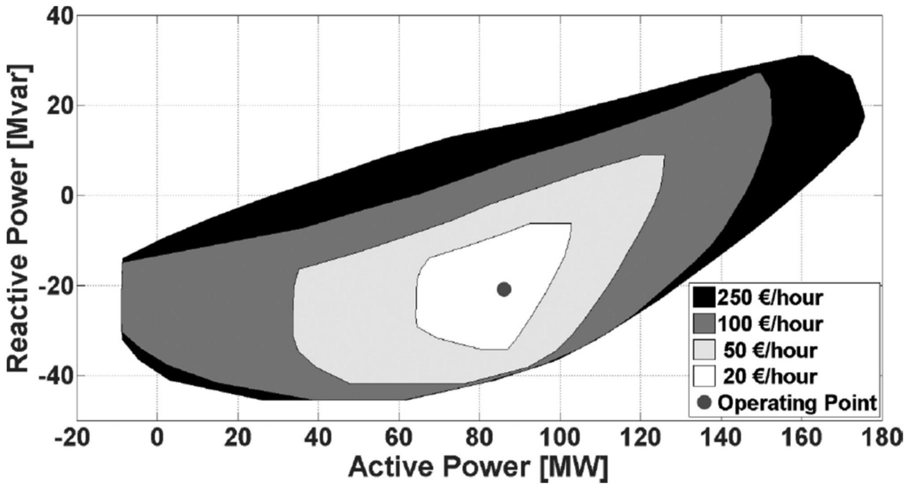

Figure 4: Feasible Operation Region [8]

In [9] the authors extend previous optimization approaches to an unbalanced three phase OPF which is especially suitable to LV grid with utilization differences between the phases. Based on the current operating point a set of directions in the two-dimensional PQ-area are separately maxed out considering feasible operating points. This process is schematically visualized in Figure 5. Afterwards a convex hull delivers the FOR at the GCP. The algorithm is compared to a RS approach and manages to detect a larger range of feasible operating points in similar computation times. Also a number of simulative evaluations on a large Italian distribution grid comprising 600 busses and also smaller parts of the mentioned grid have shown, that with an increasing grid size the performance advantage of the OPF algorithm is even further strengthened compared to an RS FSM.

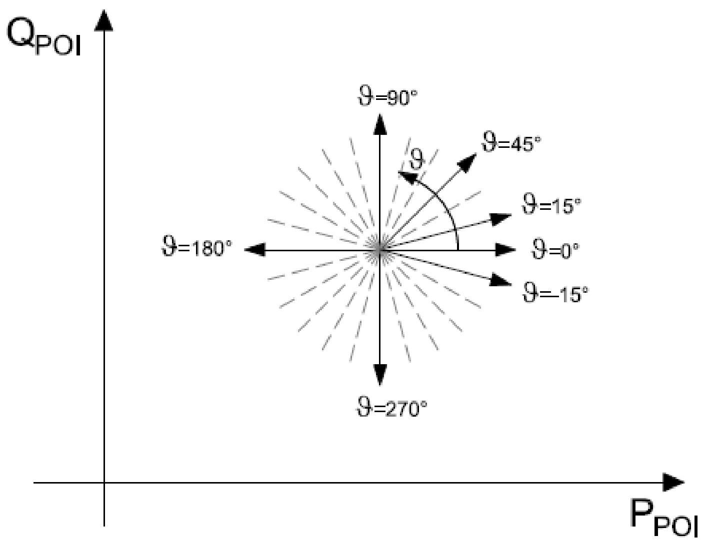

Figure 5: Directions of maximization [9]

Many approaches include an OPF either coupled with additional models or implemented into a multi staged FOR calculation process. In [10] the authors propose an optimization problem that includes the FOR estimation but extends it towards the TSO scale by optimising the flexibility activation from multiple DS. In [11] the theoretic maximum and minimum of active power output, hence neglecting losses and constraints, is used to determine the border of the FOR heuristically.

In [12] forecasts are created through a monte carlo based model before an OPF determines the FOR over time including probalistic factors considering the forecast errors. In [13] the authors use an optimization where the FOR is determined for three feeders separately and a combined area is generated. In [14] the computation is extended towards the uncertainty from tap position changes and from grid topology changes to determine the feasibility of areas within the FOR as seen in Figure 6. This is especially time intensive due to the amount of possible configurations. The full OPF based model is described in [15].

In many of the previously mentioned optimizations a linearization of the FOR at each flexible asset is required. However a verification of the made assumptions has been left out in all cases so [16] addresses this topic by comparing it to an extensive RS approach that does not require the linearization. While it can be seen that any operating point outside the determined FOR is indeed invalid, there are also a number of operating points within the area that are invalid as well and which have to accounted for. The conclusion still accounts for OPF based approaches being fitting for the daily DSO operation.

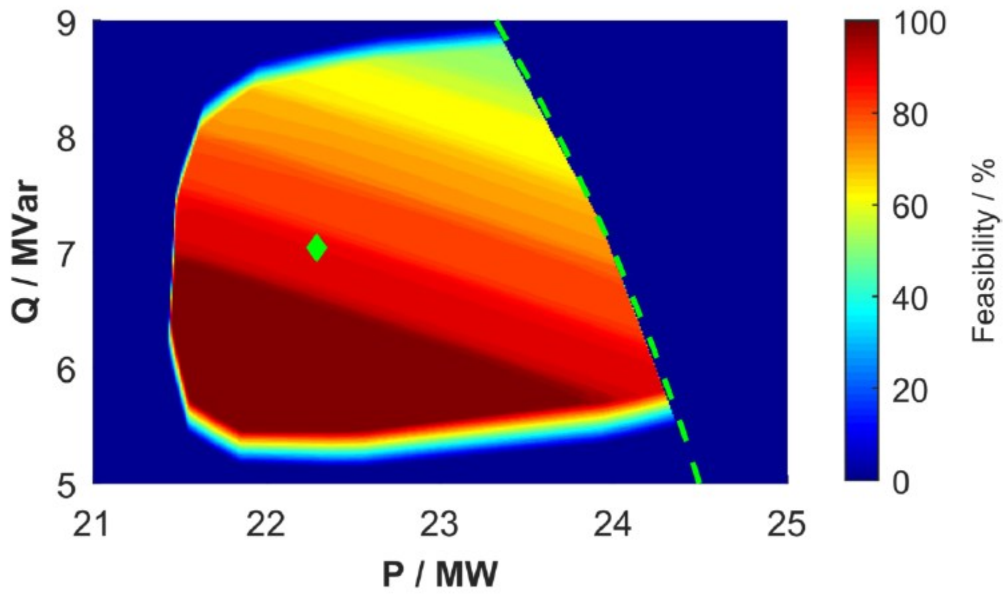

Figure 6: Topology and tap position based FOR feasibility [14]

From the literature evaluation it can be seen that a large share of the FSM approaches use optimization (often within an OPF) as a main tool within the estimation process. In many cases the determination of the FOR needs further assistance by a heuristic, that describes the process used to determine the borders of the convex hull. In opposition to that, the use of an RS approach is used less frequently due to partly longer computation times. Both approaches are partly coupled with forecasts to determine a probabilistic FOR. The simulative evaluation in [4] resulted in the key finding, that RS approaches can be adequate for smaller grids if implemented correctly. Otherwise OPF based models show a higher performance, which can especially be seen for larger grids.

3 EVALUATION OF CONTROL APPROACHES

The presented approaches in the previous Section all come with a set of advantages and disadvantages. As for the HONOR project a fitting solution has to be adapted, the approaches are all evaluated regarding a set of criteria. Afterwards a SWOT Analysis is carried out with respect to the previously defined criteria.

3.1 Evaluation Criteria

From the previously mentioned approaches the evaluation criteria scopes around the handling of the following aspects:

- Observability for the DSO / degree of known information to the DSO
- Accuracy of FOR estimation (linearization errors) / fault robustness within the estimation
- Probalistic factors: forecast errors / topology changes / transformer tap position changes
- Activation speed in emergency cases / control stability
- Model complexity / computation time / crash resistance
- Pricing of flexibility activations and market relations

3.2 SWOT Analysis of Approaches

The following Section uses the criteria from Section 3.1 and evaluates three possible approaches that were identified in Section 2. The corresponding SWOT analysis is performed with respect to the application in a practical context, namely the control center integration from the perspective of the DSO.

3.2.1 OPF based FSM Approaches

The most common approach identified was the OPF based approach, where the corresponding SWOT analysis is displayed in Table 1. The potential for detailed optimization models with technical constraints allows for a wide variety of implementation options. The approach excels for larger power systems and the integration within a control center for monitoring purposes. While there is still room for improvement, especially considering the exact FOR estimation and the model complexity, it can be identified as a fitting option for the control center integration.

Table 1: SWOT Analysis of OPF based FSM approaches

OPF	Positive impact	Negative impact
	STRENGTHS	**WEAKNESSES**
Internal factors	• Very detailed and exact computation for single operating points through the optimization modelling • Various optimization models possible with extensions • In combination with a heuristic effective FOR estimation • Cheap practical implementation (no additional hardware at assets) • Good for constant monitoring purposes in the control center	• High computation time after change of input data (Grid models, Asset Flexibility) • Linearization error • No automatic, dynamic adjustment to the measured values after sending adjustments • Dependency on central DSO and hence lower crash resistance • (Model complexity)
	OPPORTUNITIES	**THREATS**
External factors	• Quickly react in emergency situations by sending setpoints • Combination with additional module to send the setpoints to all assets • Combination with forecasts for probalistic results possible	• Risk of limited knowledge (topology changes, transformer tap position, behaviour of small assets) • Costs for compensation not known • Static calculation and setpoint adjustments: could be too slow

3.2.2 RS based FSM Approaches

In opposition to OPF based approaches the major second one were RS based approaches, where the corresponding SWOT analysis is displayed in Table 2. While there are some advantages in comparison, like more precise FOR through no necessary linearization and a simple model creation, the disadvantages have to be considered extensively. The most prominent one being the large computation time through the randomized approach and hence leaving potential for a more effective computation unused.

Table 2: SWOT Analysis of RS based FSM approaches

RS	Positive impact	Negative impact
Internal factors	**STRENGTHS**	**WEAKNESSES**
	• Estimated FOR is more precise than though OPF based approaches • No linearization error • Very simple model • Cheap practical implementation (no additional hardware at assets) • Good for constant monitoring purposes in the control center	• Cost-optimized realization of an operating point within the FOR requires another calculation step • Very high computation time after change of input data especially for larger power systems • No automatic, dynamic adjustment to the measured values after sending adjustments • Dependency on central DSO and hence lower crash resistance • Ineffective through its random nature
External factors	**OPPORTUNITIES**	**THREATS**
	• Quickly react in emergency situations by sending setpoints • Combination with additional module to send the setpoints to all assets • Combination with forecasts for probalistic results possible	• Risk of limited knowledge (topology changes, transformer tap position, behaviour of small assets) • Costs for compensation not known • Static calculation and setpoint adjustments: could be too slow

3.2.3 Dynamic FSM Approaches

A less frequently used approach in literature covers the use of dynamic controllers [7]. The SWOT analysis is visualized in Table 3. While the use of dynamic controllers is especially interesting regarding the decentralized and automated structure with very small delays, it is less fitting for the practical integration into a control center, which is the scope of the HONOR WP5. This results from the low observability and the coexistence to a larger architecture including flexibility markets etc. when including automatic controllers.

Table 3: SWOT Analysis of dynamic FSM approaches

Dynamic	**Positive impact**	**Negative impact**
	STRENGTHS	**WEAKNESSES**
Internal factors	• Dynamic behaviour adjustments within the power systems' capacities and to its topology changes • No computation necessary: Instant reaction to requested P,Q values • No dependency on a central DSO to send the setpoint adjustments	• No FOR estimation possible and therefore no monitoring by the DSO • Very complex controller structure • Expensive practical implementation through additional controller hardware • Low observability • Questionable integration into a larger architecture with flexibility markets, other unit commitments, etc. through the unsupervised action
	OPPORTUNITIES	**THREATS**
External factors	• The very quick reaction time of the controllers could be vital in emergency situations • Combination with an additional module for FOR estimation (OPF- or RS based)	• Faulty controller implementations in the field • Costs for compensation not known

4 SPECIFICATION OF MOST PROMISING APPROACH AND SIMULATIVE EVALUATION

In this Section the most promising of the mentioned approaches in Section 3 is identified. Following that the implemented model is described and simulation results are displayed.

4.1.1 FSM Approach Specification

The SWOT analysis delivered a review on the different concepts, that were previously elaborated. From the work it can clearly be seen, that one approach is specifically fitting for the targeted implementation within HONOR: OPF based approach.

While dynamic approaches allow for a very fast reaction time, the costs of such an implementation with the complexity of it make it a less feasible option. Also as the focus within HONOR is on the DSO control center perspective, it is less fitting considering the demands for a control system integration and system monitoring demands.

RS-approaches deliver similar results to OPF based ones and could be feasible options as well, but the lacking algorithm efficiency through its undirected nature results in an ineffective use of computation capacities.

The choice has therefore been made towards the usage of an OPF based approach. The optimization models can be created and adjusted to the circumstances and hence can robustly react to changes in the input data like additional technical or market related constraints.

4.1.2 Model Description and Simulative Evaluation

The implemented model in HONOR is described in D5.1 [1] and in a corresponding publication [2]. This Subsection gives a brief overview on the algorithm and shows simulation results. However for more details on the elaborated contents the mentioned references deliver specific model descriptions.

The implemented FSM in HONOR can be described as a Checkerboard-OPF. As visualised in Figure 7, the PQ area at the GCP is covered with a grid of operating points where the feasibility of each one is checked through an OPF and the results deliver the FOR. The outside boundary is thereby set through the theoretic maximum are (no grid constraints, max feed-in or load possible). Also the mentioned synergies in Section 2.1 between FOR estimation and the realization of an operating point through the setpoint determination is merged into one process as every single operating point already has a calculated setpoint for every flexible asset.

The optimization respects the voltage limits at busses, power flow limits in branches, general power flow equations, active and reactive limits of the generators, and N-1 security constraints for lines. The high computation time is reduced through a parallel computation. An exemplary application on the Cigre MV Benchmark Grid [17] can be seen in Figure 8 though more details on the simulation are presented in [2] as previously mentioned.

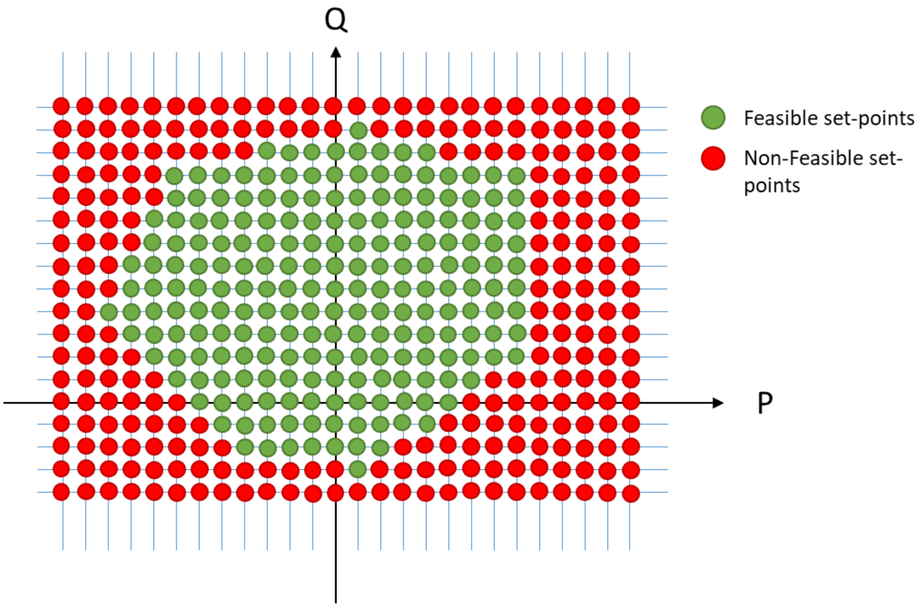

Figure 7: PQ Area through Checkerboard OPF

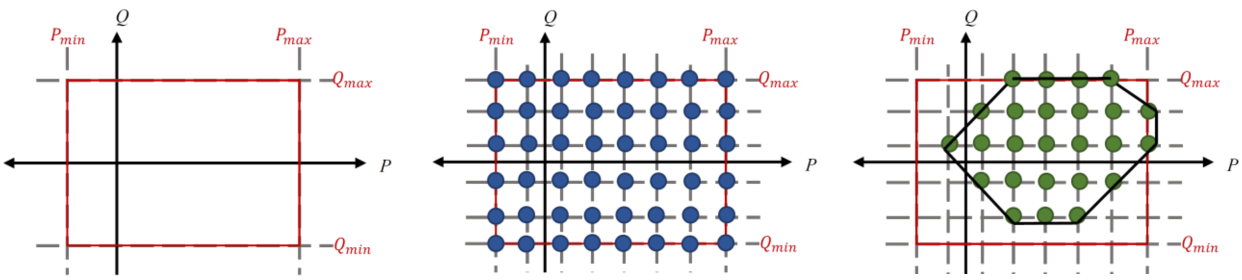

Figure 8: Example for FOR Estimation

5 CONCLUSION AND OUTLOOK

This Deliverable provides a valuable review on algorithms considering the provision of flexible power flow adjustments at the GCP. It presents dynamic, probalistic, heuristic and optimization approaches for the provision of a FSM and the corresponding unit control. The addressed approaches are classified and evaluated with a SWOT analysis. As a consequence the recommendation for the usage of an OPF based approach in the context of the control center integration is given.

Future work will cover the implementation of an OPF based concept in a laboratory demonstration. A control center will be equipped with the algorithm in order to determine the range of potential adjustments and hence the FOR. If the operating point has to be changed within the FOR, then the operator can give the command in his graphical user interface (GUI). The corresponding setpoint for each flexible asset is forwarded to the unit and the operator can monitor this process in his GUI. Within the laboratory setup the control center algorithm will be used on a MV grid in a real time simulation which is coupled with a physical LV grid with flexible units, which will be controlled through the control center based on the algorithms outputs.

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FUNDING

This document was created as part of the ERA-Net Smart Energy Systems project HONOR, funded from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 646039 and no. 775970 (RegSys 2018).