WPD INNOVATION
Transforming the electricity network

Harmonic Mitigation

NIA Project Closedown Report
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1. Executive Summary

Harmonic Mitigation was a Network Innovation Allowance (NIA) funded project that was carried out between September 2019 and February 2022 with a total budget of £425,000. The project aimed to investigate, through dynamic power systems analysis modelling, the availability and suitability of using existing inverters connected to the Western Power Distribution (WPD) network to manage harmonic levels by providing harmonic compensation as an ancillary service during times of low irradiance through the creation of a control algorithm. This was a timely project as harmonics are becoming a concern across all UK electricity distribution networks, attributable to the increasing number of nonlinear devices being connected to the network each year.

The project carried out four Work Packages. The first Work Package involved undertaking an extensive literature review on the already developed approaches to managing network harmonics, in addition to the creation of the network model and initial base studies. The modelling environment was established to be carried out in MATLAB/Simulink after undertaking numerous power flow studies and frequency response checks. These were validated by comparing the model to SCADA data and an existing WPD DIgSILENT PowerFactory model of the chosen network.

Work Package two designed, developed and implemented the control algorithm that would be used to provide existing Photo Voltaic (PV) inverters with Active Filter (AF) functionality for a single inverter. The development of AF functionality comprised of determining pertinent control parameters that allowed the PV inverter to inject harmonic components of equal magnitude but opposite polarity with respect to the existing harmonics on the network feeders. Additional controls were incorporated to ensure that the inverter rating was never exceeded when providing harmonic compensation. The developed algorithm in this Work Package was deemed successful as it managed to reduce voltage harmonics within the network model.

Work Package three took the designed algorithm a step further by evolving it so that it could operate for numerous inverters in an independent operation or through a coordinated approach. It was identified this approach further reduced feeder harmonics because of more inverters being utilised i.e. more available capacity from each inverter.

Work Package 4 incorporated the algorithm and applied it to a physical inverter. This resulted in carrying out Hardware In Loop (HIL) analysis that involved real time simulation in a laboratory environment. The results generated were assessed and analysed compared to the results seen in Work Package 2 in order to identify the correct operation from the inverter. Some limitations were identified, based on equipment availability rather than the work already produced, however, this was overcome and the modifications made were validated within the Work Package. Consequently, the HIL testing verified the correct operation of the developed control algorithm developed throughout the project with very close alignment to the results observed in Work Package 2.

Harmonic Mitigation has been delivered within the initial timescales and within its stated budget. During this project, all aims, objectives and success criteria have been met. Further information such as project documentation, in depth Work Package reports and the technical closedown report can be found on the WPD Innovation project website:
[Western Power Distribution - Harmonic Mitigation]

2. Project Background

It is expected that due to the increasing number of non-linear loads, including some Low Carbon Technologies (LCTs) being connected to the distribution network, system harmonics can become a challenge for Distribution Network Operators (DNOs). Existing solutions for managing harmonics are not suitable for dynamic networks with varying operating conditions and can also be very expensive. One of the most common solutions to mitigate harmonics consists in installing harmonic filters. These devices are designed to absorb a well-defined band of harmonics by providing a low-impedance path for particular frequencies but falter, having an inefficacy under all operating conditions. An AF is an alternative solution to mitigate excessive harmonic levels in the distribution network where it consists of a controlled power converter to absorb harmonic components. AFs, however, are not commonly used at the distribution network level, due to the cost of this technology. Therefore, it is important to find alternative solutions in order to be able to manage harmonic levels in the network in a cost effective way.

Traditional methods of overcoming technical constraints that arise from increased LCT connections involve standard network reinforcement that is costly and is usually passed on to the end customer. Therefore, it is now common practice to develop innovative solutions that increase the utilisation of existing network assets to defer network reinforcement. Consequently, the fundamental objective of this project was to determine how effective a control algorithm can be when deployed on PV inverters to mitigate harmonics when capacity is freely available.

Swansea University’s Faculty of Science and Engineering department carried out the project with PSC being on board with the project in a consultancy role.

3. Scope and Objectives

The project has met the objectives set out when the project was first registered and is outlaid below in table 3.1.

Table 3-1: Status of project objectives

Objective	Status
• Completion of a literature review on existing solutions for managing network harmonics.	✓
• Creation of an algorithm that by controlling each inverter individually is managing the network's harmonics.	✓
• Creation of an algorithm that by controlling all inverters in the network is managing the network's harmonics.	✓

4. Success Criteria

The project has performed and met all of the success criteria outlined at the registration phase of the project. The success criteria is shown in table 4.1 below.

Table 4-1: Status of project success criteria

Success Criteria	Status
• The developed algorithm can improve the harmonic levels when controlling one converter.	✓
• The developed algorithm can improve the harmonic levels when controlling multiple inverters.	✓
• The Hardware in the Loop (HIL) testing confirms the correct operation of the algorithm and successful response from the inverter.	✓
• Knowledge is gained on whether the harmonic levels in the network can be improved by controlling existing inverters.	✓
• Conclusions are made on whether a demonstration project is recommended.	✓

5. Details of the Work Carried Out

This project set out with the aim to create a control algorithm that could act as an ancillary service to provide harmonic compensation at single and multiple PV inverter locations when capacity is available. In addition to this, current literature was captured underlying the importance of harmonics, their formation and effect on the distribution network along with current mitigation practices. The project has established that this control algorithm can effectively reduce voltage Total Harmonic Distortion (THD) present at a Bulk Supply Point (BSP). This methodology was firstly applied to a single PV inverter connected to a model of network in WPD’s South West licence area. With results showing that THD can be reduced through a single inverter, the development evolved into creating an algorithm that could control multiple inverters individually with a further expansion being made into looking at controlling the inverters in a coordinated way. With additional inverters able to be utilised, an increased reduction of voltage THD is observed.

The work within the project was broken down into four Work Packages outlined below:

5.1. Work Package 1 - Literature Review, Model Creation and Base Studies

Work package one commenced on taking an in depth review of current literature surrounding harmonic, their adverse effects and mitigation methods a long with creating the initial network model within the chosen simulation software, MATLAB Simulink. The result of the literature review provided an in depth analysis of current mitigation strategies to harmonics by using different types of filters. A cost analysis was produced showing the expenditure needed to incorporate passive and active filters onto a network based on the filters’ rating as seen in Figure 5.1. It was also determined that due to the sophistication of AF controls, it is possible to embed AF operation within present inverters, subsequently saving costs of buying a dedicated AF.

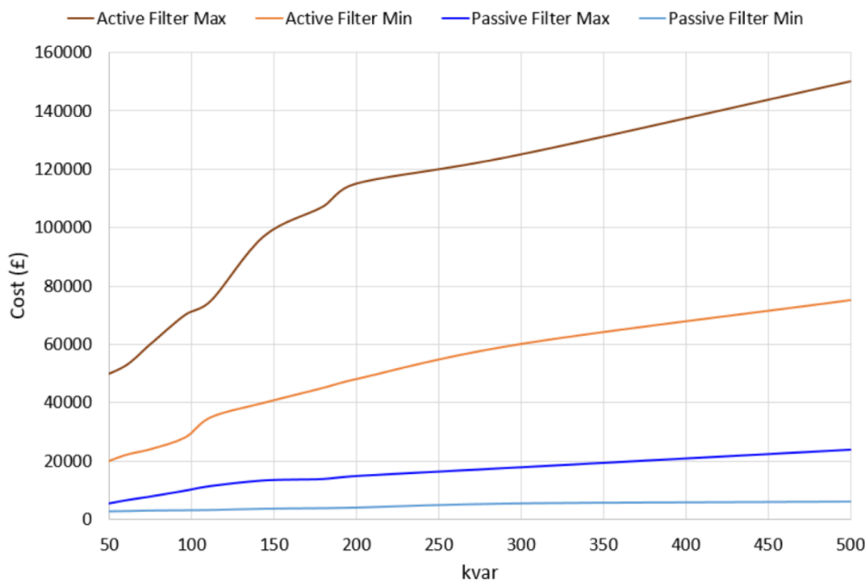

Figure 5.1 Summary of filter costs based on their rating

The second part of this Work Package consisted of creating and validating a network model of the actual physical system. The Tiverton 33kV network was chosen and was incorporated into MATLAB Simulink. This software was chosen due to it having available component libraries for power system modelling and control systems, the ability to carry out automated analysis for performance parameters like THD and being able to integrate with real time simulation software that was used in Work Package 4. Figures 5.2a and 5.2b show the Tiverton Single Line Diagram (SLD) and MATLAB/Simulink equivalent.

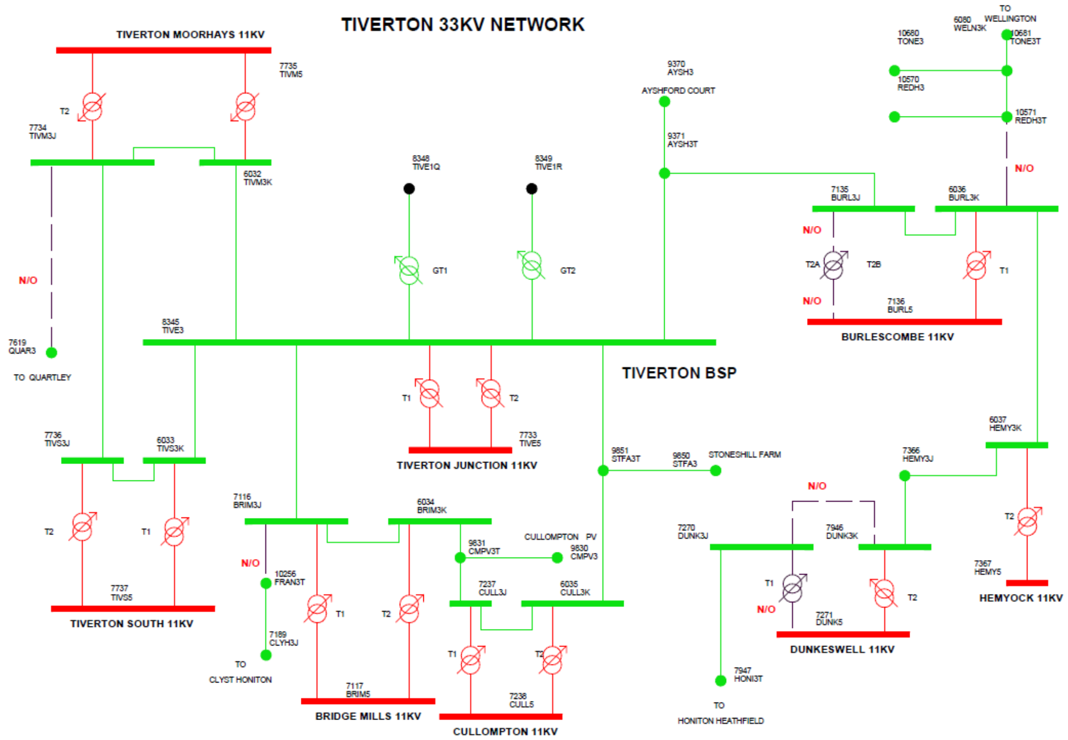

Figure 5.2a SLD of the Tiverton Network

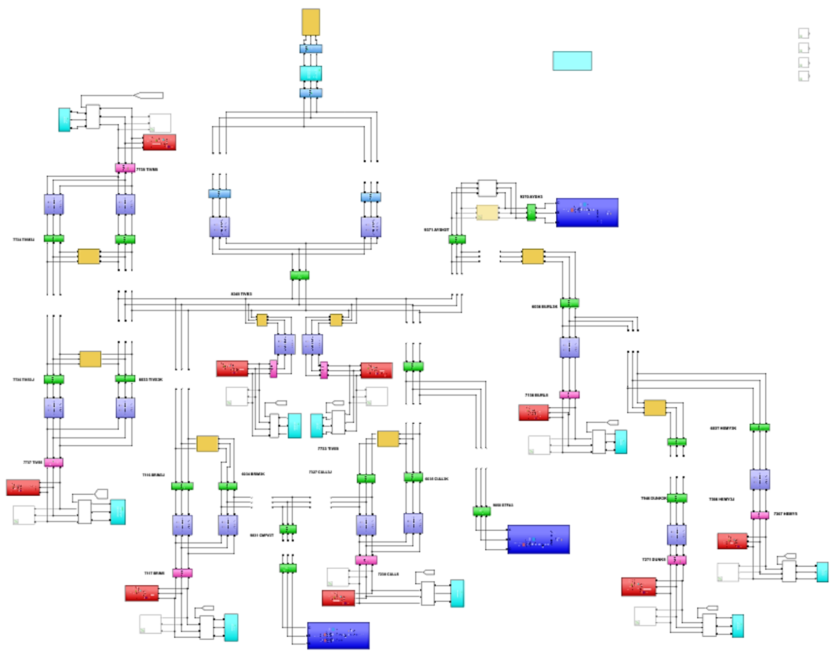

Figure 5.2b Overview of the MATLAB/Simulink model

As a new network model was created in a new piece of software, it had to be validate in order to make sure the work produced further afield was legitimate. This was carried out by comparing results (power flows, bus voltages) to an already accepted model in PowerFactory and SCADA data. The results generated showed a very good agreement between the PowerFactory model. Some discrepancies were observed when comparing against the SCADA data, however, this was also true when comparing against the PowerFactory model. It was deduced that there were some inaccuracies in the models' assumption. An example being tap changer values not being present in both models whereas they are in SCADA data.

5.2. Work Package 2 – Algorithm Design, Development and Implementation for single inverter control

Work Package 2 started by designing the algorithm that would aim to achieve AF functionality through single inverter control. The inverter would utilise AF by using excess capacity that wasn't being used when fundamental power wasn't optimal. The ideology for this work package is shown below:

- Control algorithm specification
- Algorithm design and development
- Testing and validation
- Operational checks

It was apparent from the start that this mitigation method was to be used an ancillary service only. Providing fundamental power to the network was the inverters' top priority and providing harmonic compensation was to only be provided if the inverter had capacity that could be capitalised. Therefore, specifications needed to be made to would be considered by the control algorithm. The main specifications are outlined below in table 5.1.

Table 5.1 Control Algorithm Specifications

Control Algorithm Specifications
The algorithm does not cause any thermal, voltage, fault level or other constraint in the network.
The rating of the PV inverter is never exceeded.
A measurement point shall be chosen that regulates the amount of harmonic injection provided by the inverter.
Consideration shall be taken into the acquisition of measurement data and any phase shift due to the interface transformer.
The control algorithm needs to be demonstrated through an inverted under multiple operating conditions that include variable inverter output power and variable system harmonic levels
In order for the benefits of the algorithm to be realised.

There were key stages that were introduced into the process of designing the algorithm to incorporate AF functionality. The core principles of how the algorithm functions are noted below:

- DC voltage regulation – Calculates the reference current for the inverter at the fundamental frequency
- Current regulation - Filters and extracts harmonics, calculates available capacity and controls fundamental power
- Pulse Width Modulation (PWM) – Used for signal generation
- dq transformation and measurement – dq transformation used to simplify control calculations

- Reference voltage transformation from dq frame to abc frame – used to recover three phase component values

With these design principles incorporated, testing and validation was essential in order to prove the algorithms legitimacy. Steps were taken in order to reduce the amount of variables in question; initially individual harmonics were analysed, then a small group of them before all of the harmonic components used in the algorithm. Constant solar irradiance was used and the inverters fundamental power output was run at 50% in order to ensure harmonic compensation could be provided.

Validation was carried out by using the same methodology and work produced in Work Package 1. The algorithm was validated by comparing the harmonic distortion on the network under two operating principles:

- Running the model with no harmonic mitigation
- Running the model with Harmonic mitigation

Frequency distribution charts of the magnitude of the harmonic current were compared. This includes all harmonic components (5^{th} through 13^{th}). Fast Fourier Transform (FFT) charts for voltage and at the 33kV BSP and current at the feeder of measurement were also compared. These charts would show the average frequency window for the full time period. Furthermore, the impact of voltage THD at the BSP were also assessed.

The algorithm was run over a 21 day (simulation) period and demonstrated a significant reduction to harmonic current levels on the network and voltage THD was seen to reduce by up to 33.8%.

5.3. Work Package 3 - Algorithm Design, Development and Implementation for multiple inverter control

Work Package 3 began by further developing the algorithm so that it could be utilised for several inverters rather just a single unit. The differentiating factor between Work Package 2 and 3 is that the harmonic current flows are more complex and that multiple current measurements were tested. It was concluded that the best measurement point was the LV side of the 132/33kV transformers due the measurement containing the all the loads in the system that contributed to the current components.

Further validation had to take place when incorporating the additional inverters into the algorithm. Further contingencies took place with the algorithm being consistently stable throughout bar one contingency, where a feeder was lost by means of a circuit breaker opening. Supplementary analysis showed that resonance occurred at the 15^{th} order harmonic, which was excited by a small current produced by the inverters. A subsequent filter was added to mitigate this error.
It was identified that on some rare occasions, transformers connected to the inverter outputs would sometimes exceed their rating. In order to comply with one of the control specifications, it was decided to introduce at transformer coefficient (k_t) that would curtail harmonics whenever the transformer rating was nearing its limit. This introduction did have an effect on algorithms' ability to reduce harmonics compared to when it was not involved, however it still caused a significant reduction on the voltage THD compared to the base case.

5.4. Work Package 4 – Hardware In the Loop (HIL) Testing

Work Package 4 introduced the use of hardware to be used in simulations. This is where a real physical inverter was used in the loop for analysis. A few months were dedicated to set up the new model and get the inverter and the real time emulator integrated so that analysis was feasible. Issues were encountered throughout this period as it was discovered that, given the scale of the network model used in MATLAB/Simulink the best sampling time to run the model exceeded that of the time required to run the model in real time resulting in overruns and glitches. This required simplification of the network model in order to achieve the desired running time for real time simulation. In order to maintain some validity with the model, tests were carried out and comparisons were made of the simplified and complex network to ensure continuity moving forward. The simplification that was introduced did not impede on the accuracy of the results.

Another issue encountered was that real time simulation does not allow using interpolation of PQ data similarly to the Simulink model, as only integer multiples of the time step can be used. This resulted initially in a shifting of the results in RT-LAB compared to simulation. This was finally corrected by strategically duplicating one data point out of every ten for the high resolution power quality data. This however, was not the case for SCADA data as its resolution was lower and did not require any interpolations.

6. Performance Compared to Original Aims, Objectives and Success Criteria

6.1. Objectives

Objective	Status	Performance
• Completion of a literature review on existing solutions for managing network harmonics.	Complete	The Literature Review was completed and provided a detailed summary of previous research and development that can beneficially be built upon in the work Swansea University undertook. This outlined the principle devices used to mitigate harmonics, and for active filters described the main functional blocks. In addition, previous work of implementing harmonic mitigation algorithms in multi-functional inverter controllers was researched and reported.
• Creation of an algorithm that by controlling each inverter individually is managing the network's harmonics.	Complete	The development of the AF functionality consisted in choosing appropriate control algorithms and parameters that allows the PV inverter to inject harmonic components equal in magnitude and opposite in phase with respect to existing harmonics on the feeder. As a result, cancellation of harmonic currents is obtained at the point of common coupling (PCC), thus leading to a reduced harmonic distortion in the upstream network. The voltage THD at the 33 kV BSP is reduced up to 24% (approximately one quarter of the original value).
• Creation of an algorithm that by controlling all inverters in the network is managing the network's harmonics.	Complete	When compared to the single inverter operation, the use of the three inverters leads to a further reduction of the voltage THD at 33kV BSP, thus indicating the positive contribution of the two additional inverters. There were some areas were reduction in voltage THD reduced by 55%.
• Carry out HIL testing on an inverter in a laboratory environment to determine algorithms impact.	Complete	The HIL testing results have been documented in the Work Package 4 report. It was demonstrated that the inverter has the capability to inject harmonic currents (5th, 7th, 11th and 13th). This has been authenticated through time domain analysis and FFT calculations.

6.2. Success Criteria

Success Criteria	Achieved	Performance
• The developed algorithm can improve the harmonic levels when controlling one converter.	Yes	The voltage total harmonic distortion (THD) at the 33 kV BSP is reduced up to 24% (approximately ¼ of the original value).
• The developed algorithm can improve the harmonic levels when controlling multiple inverters.	Yes	When compared to the single inverter operation, the use of the three inverters leads to a further reduction of the voltage THD at 33kV BSP, thus indicating the positive contribution of the two additional inverters. There were some areas were reduction in voltage THD reduced by 55%.
• The Hardware in the Loop (HIL) testing confirms the correct operation of the algorithm and successful response from the inverter.	Yes	The HIL testing has showed a similar performance to the one experienced in Work Package 2. This was key to prove the inverters performance as it is validated against simulations.
• Knowledge is gained on whether the harmonic levels in the network can be improved by controlling existing inverters.	Yes	Throughout Work Packages 2 and 3 it has been covered extensively that inverters providing an ancillary service for harmonic compensation reduce and improve network harmonic levels
• Conclusions are made on whether a demonstration project is recommended.	Yes	Conclusions have been drawn on what work could be carried out in future work. More detail on future recommendations are captured in section 13.

7. Required Modifications to the Planned Approach during the Course of the Project

There were very minor modifications that were made to the project. Any modifications that were made did not have any impact on the project's delivery.

8. Project Costs

The final costs for the Harmonic Mitigation project can be seen in table 8.1 below.

Table 8-1: Project Spend

Activity	Budget	Actual	Variance
WPD Project Management	£76,776	£89,389	-16.4 %
Contractors	£309,928	£295,526	4.6 %
Contingency	£38,670	£12,613	67.4 %
Total	£425,374	£384,915	9.5 %

Although the whole project came in under budget, the WPD Project Management budget had a slight overspend. This was because more time was used at the early stages of the project, thus creating a slight offset for the remainder of the project. The contingency pot was utilised because of this. The anticipated costs for contractors was less than first foreseen, resulting in an underspend of 4.6%. Overall, the project came with an underspend of 9.5%.

9. Lessons Learnt for Future Projects

Workstream	Learning Detail
WP1	It has been shown that MATLAB/Simulink software can be used to model both the 50 Hz behaviour and the harmonic behaviour of the Tiverton Network accurately. The modelling of the 50 Hz components is straightforward as identical component blocks are present in MATLAB/Simulink and DIgSILENT PowerFactory. For harmonic analysis, MATLAB/Simulink showed some limitations. For example, it is not possible to model frequency-dependency of components, however, these limitations were overcome by modelling these components separately.
WP1	Further difficulties were observed with numerical stability of the time domain solver and these were resolved by the introduction of large shunt resistors such that they have no (or absolute minimum) impact on the simulation results For example, it was established that multiple current sources cannot be connected to the same node, unless shunt resistors are used. The dynamic model used for loads also require a large resistance connected in parallel. The resistances used in the model are greater than 104 Ω.
WP1	The largest time-step that can be used with the current Simulink model is 8 μs, due to the presence of short lines modelled using distributed parameters but this small time-step will be equally required for the active filter algorithms in the later stages. As a result, running an EMT simulation for the Tiverton Network is computationally intensive. Running one day data set takes about 20 min, using a 32 GB RAM, SSD, 1 TB Desktop PC with i-7 processor. Running a time domain simulation for one week takes slightly above 2 hrs. The size of the data generated for a week simulation is about 8 GB. To limit the size of data generated, a one-month study will be run using four different simulations, by feeding different SCADA and power quality data set to the same network model.
WP1	Both the power quality monitor data and the SCADA data are used to develop dynamic models, However, they present a significantly different time resolution. Therefore, appropriate scaling needs to be applied when the data are imported to ensure that the PV farms and the load models are temporally aligned.
WP2	An automatic gain function is essential for the inverter not to exceed its current rating. At times of high irradiance and subsequently high inverter output, the inverter was known to exceed its current

	rating. An automatic gain function was incorporated into the algorithm to restrict the harmonic injection from the inverter under this scenario.
WP2	Harmonic mitigation via single inverter operation can reduce the voltage THD by up to 33.8%. The average reduction over a three week period in October was observed to be 15.7%. Therefore, harmonic mitigation is achievable.
WP2	Transformer losses increase whilst AF functionality is implemented. These are however, small scale transformers.
WP3	For the system under study, the best current measurement point is the bulk supply point, P_1. However, it is possible to have multiple measurement points and modify them, depending on system operating conditions or other events (for example, faults on a feeder). Using a different current measurement point will change the duty on each inverter (both increase and decrease is possible).
WP3	Introduction of a low-pass filter into the input voltage signal results in a more tuned control operation by avoiding voltage harmonics to be fed to the controller and in return causing distortion to the inverter output current.
WP3	The automatic gain and the transformer loss coefficient limit the amount of harmonic current injected. This keeps the overall inverter current and transformer losses within rated levels.
WP3	The inverter has an impact on the equivalent system impedance, in particular at the frequencies of current injection, due to a combination of inverter output filter and control loops. The inverter equivalent impedance changes when AF operation is activated, due to the introduction of additional control loops, compared to normal operation. The impact decreases with increased electrical distance in the point of interest (i.e. where equivalent impedance is calculated).
WP4	The PELab capability to inject harmonic currents has been demonstrated by time-domain analysis and by FFT calculations: the PELab can be controlled to inject the harmonics of interest for the project (5^{th}, 7^{th}, 11^{th} and 13^{th}).
WP4	The minimum sampling time achievable to run real-time-simulation is 20 µs. This means that very short lines included in the Simulink model cannot be modelled using distributed parameters, as they require 8 µs sampling time. These lines have therefore been replaced with pi-sections. After adding the control algorithms for the inverters, this sampling time was increased to 100 µs.

WP4	Real-time simulation does not allow using interpolation of PQ data similarly to the Simulink model, as only integer multiples of the time step can be used. This resulted initially in a shifting of the results in RT-LAB compared to simulation. This phenomenon has been corrected by duplicating one point every ten for the high-resolution power quality data. The SCADA data could be imported by using the same resolution as in simulation, as their resolution is lower and does not require any interpolations.
WP4	The original network model is too large to be handled by the equipment available. Therefore, the network was reduced, and an equivalent load model was used. This observation indicates that the complexity of real-time analysis increases very rapidly with an increasing network model.
WP4	The simplification introduced does not affect the accuracy of the results. More specifically, both fundamental harmonics components match very closely the original network model used in previous work packages. Therefore, it was concluded the reduced network could be adopted to verify the performance of the harmonic mitigation algorithm.

9.1. Project Management Learning

Learning Detail	Outcome
Consideration of computational equipment at the project scoping phase.	It was encountered late on in the project that some of the equipment to be used for real time simulation did not have the computational capacity to handle the network model. It has been learnt that such consideration will be made in future projects.
Consideration that the algorithm would change from Work Package 2 to Work Package 3.	The final deliverable, Work Package 4 was centred on comparing its generated results to results seen in Work Package 2. However, Work Package 3 saw further improvements to the algorithm that had to be taken out during Work Package 4.
Consideration of multiple inverters for HIL.	Consideration of multiple inverters for HIL would mitigate the above point. If the budget was increased during the planning stage to accommodate additional inverters, more in depth analysis would have been able to be undertaken and the opportunity to see the algorithms effectiveness with multiple inverters in the loop could have come to fruition.
More robust contingencies for equipment failure.	The early stages of Work Package 4 saw some inverter components fail, resulting in the equipment being out of action for around 4 weeks. Although the project did not halt, with focus moving to Software in the Loop (SIL) analysis, better contingencies could have been made to deal with this possible risk.

10. The Outcomes of the Project

The main outcomes for the project are outlined below. For convenience, they have been split into outcomes from each respective Work Package.

10.1. Work Package 1 Outcomes

- Literature review – This literature review was delivered as a report and addressed how distribution connected inverters associated with renewable energy resources may provide harmonic compensation as an ancillary service. Investigations were made and analysis was undertaken on the importance of harmonics and the different type of filters that are used to reduce them.
- Model Development – The model development compromised of the Work Package 1 report. This report documented the creation and validation of the modelling environment within MATLAB/Simulink. An in depth analysis of the stages taken to authorise the model was given including all electrical characteristics.

10.2. Work Package 2 Outcomes

- Work Package 2 report – This report documented the development of the control algorithm that would be utilised on a single inverter to provide harmonic compensation. Information captured in this report centres around the choices of control parameters used to generate the correct level of harmonic compensation.
- Work Package 2 slide pack – This slide pack accompanies the Work Package 2 report and expresses the content in a more visual field of view.

10.3. Work Package 3 Outcomes

- Work Package 3 report – The Work Package 3 report further developed the work carried out in the previous work package. This included adding the AF functionality to multiple inverters rather than a single inverter unit within the network model. It was also detailed within the report the improvements made to the algorithm compared to the designed one in Work Package 2.
- ISGT Europe 2021 Paper – "Harmonic Mitigation as Ancillary Service Provided by Multiple Photovoltaic Inverters". This academic paper described the work carried out up until Work Package 3. Presented at the Innovative Smart Grid Technologies Europe 2021 conference and published on the IEEE online library, this paper detailed the specific control theory that was behind the algorithm and showed its effectiveness in reducing network harmonics. The paper can be purchased and read here: Harmonic Mitigation as Ancillary Service Provided by Multiple Photovoltaic Inverters | IEEE Conference Publication | IEEE Xplore
- CIGRE 2022 Kyoto Symposium, Japan – "Use of PV inverters to mitigate harmonic levels on distribution systems" Similar to the ISGT paper, this symposium report included an updated control algorithm with additional results due to the further supplements added to the control algorithm. Due to be presented April 2022.
- ENIC 2021 Poster – this poster was presented at the Energy Networks Innovation Conference 2021 where the project was exposed to a high number of stakeholders across industry.

10.4. Work Package 4 Outcomes

- Work Package 4 report – The Work Package 4 report captured the analysis undertaken to integrate the control algorithm into a physical inverter and test it on a network model through real time simulation. This included the encountered problems, the steps taken to resolve & mitigate them and a comparison exercise of results to those seen in Work Package 2.
- RTLab21 Presentation – A presentation was given at the OPAL-RT RT21 conference. The presentation had a focus on how the real time simulation element of the Work Package functioned and the steps involved to incorporate the algorithm into the system and run successful simulation.

The full learning has been disseminated via WPDs Innovation website page where access to full work package reports is freely available at: www.westernpower.co.uk/Harmonic-Mitigation

11. Data Access Details

No new data was generated from the project, only existing data had been used to carry out the project such as SCADA and Power Quality data extracted from WPDs systems.

12. Foreground IPR

The following foreground IPR generated from the project is outlined below:

- Control Algorithms
- Work Package reports

13. Planned Implementation

Based on the projects conclusions and outputs obtained through simulations of the network model, the Harmonic Mitigation algorithm has shown the potential to be used as an ancillary service at PV inverter locations to utilise excess capacity. Because of this learning, a number of follow on possibilities have been identified on future work that could be carried out. Some of the possibilities are outlined below;

- Introduce communication functionality between inverters. Although the current project found an optimum working pattern, each inverter can be controlled in automatically coordinated fashion such that the level of gain in each is adjusted considering not just its own capacity but also of the other inverters. This could be further enhanced by adjusting gain on harmonic group basis in both directions in multiple inverters, i.e., different inverters providing their compensation capacity for different group of harmonics.

- Introduce adaptability to change feedback points as required. This could be done automatically as part of wider control strategy such as communication between different controllers and/or other network control/automation parameters. Using a different current measurement point will change the duty on each inverter (both increase and decrease is possible).

- Extend HIL testing to include multiple inverters. Current project considered HIL testing of one individual inverter due to equipment availability. However, a full comparison with the Simulink results would need the use of multiple inverters connected to the grid emulator. More powerful real-time digital simulation platforms will be required that can interface multiple devices and cover a larger network model.

- Employ a Power Hardware-in-the-Loop (PHIL) testing, possibly including a PV panel on the dc side of the power converter. This would necessitate use of power amplifiers to interface the grid emulator to the inverter in order to allow power flow through the inverter.

The various stages of the project have shown that there are many areas where issues are likely to crop up. Therefore, it is recommended that further verification tests (such as with multiple inverters) are performed such that the algorithm is subjected to more realistic network conditions (use of actual instantaneous timeframe instead of condensed time). Following this, the algorithm can be tested in the field by employing limited number of inverters initially during low irradiation period followed by full day testing.

14. Contact

Further details on this project can be made available from the following points of contact:

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Glossary

Abbreviation	Term
AF	Active Filter
BSP	Bulk Supply Point
DNO	Distribution Network Operator
ENIC	Energy Networks Innovation Conference
FFT	Fast Fourier Transform
HIL	Hardware in the Loop
ISGT	Innovative Smart Grid Technologies
NIA	Network Innovation Allowance
PCC	Point of Common Coupling
PHIL	Power Hardware in the Loop
PQ	Power Quality
PV	Photo Voltaic
PWM	Pulse Width Modulation
SCADA	Supervisory Control and Data Acquisition
SIL	Software in the Loop
THD	Total Harmonic Distortion
WPD	Western Power Distribution

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