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NIA Project Close Down Report Document

Date of Submission

Jun 2022

Project Reference

NIA_WPD_043

Project Progress

Project Title

Harmonic Mitigation

Project Reference

NIA_WPD_043

Funding Licensee(s)

WPD - Western Power Distribution (East Midlands) Plc

Project Start Date

September 2019

Project Duration

2 years and 6 months

Nominated Project Contact(s)

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Scope

The project has been split into the following Work Packages:

- Work Package 1 – Literature Review, Model Creation and Base Studies: As part of this Work Package, a detailed literature review will be done on the already developed approaches to managing harmonics in the network and any algorithms that relate to the proposed approach in the Harmonic Mitigation project. Additionally, the MATLAB model of the network that will be analysed will be created and validated. The base case harmonic studies will also be run in this Work Package, providing the reference that will be used to assess the algorithms impact on harmonic levels in the following Work Packages.
- Work Package 2 – Algorithm Design, Development and Implementation for single inverter control: This Work Package will involve the design and implementation of the algorithm that will be able to control each inverter individually.
- Work Package 3 - Algorithm Design, Development and Implementation for multiple inverter control: As part of this Work Package, the algorithm will be further developed so that it can control multiple inverters.
- Work Package 4 – Hardware In the Loop (HIL) Testing: In this Work Package, the developed solution will be used in order to demonstrate the operation of the algorithm on an actual inverter at a university laboratory. As part of this test, the model of the network used in Work Package 2 will be used to simulate the test network and an actual inverter will be connected to this simulated network. The operation of the algorithm and control of the inverter will then be tested.

Objectives

The main objectives of the project are:

- Completion of 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.

Success Criteria

The project will be considered successful if:

- 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 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.

Performance Compared to the Original Project Aims, Objectives and Success Criteria

Carry out a literature review on existing solutions for managing network harmonics (Complete)

The Literature Review1 was completed in Jan 2020 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.

Create an algorithm that can control each inverter individually and reduce network harmonics (Complete)
The development of the active filter 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 effectiveness of the proposed algorithm was verified for varying harmonic levels, for varying levels of irradiance and for both positive- and negative sequence components. The voltage Total Harmonic Distortion (THD) at the 33 kV BSP is reduced up to 24% (approximately ¼ of the original value). This result is justified by observing that the voltage harmonics measured at the BSP result from the contribution of both background distortion and harmonic injection from loads connected through other feeders

Create an algorithm that can control all inverters in the network and reduce network 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.2 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 Fast Fourier

Transform (FFT) calculations.

The developed algorithm can improve network harmonic levels by controlling a single inverter.(Achieved)

The voltage THD at the 33 kV BSP is reduced up to 24%(approximately ¼ of the original value).

The developed algorithm can improve network harmonic levels by controlling multiple inverters. (Achieved)

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 HIL testing confirms the correct operation of the algorithm and successful response from the inverter. (Achieved)
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.

Conclusions are drawn on whether a demonstration project is recommended. (Achieved)
Conclusions have been drawn on what work could be carried out in future work. More detail on future recommendations are captured in section 10.

Required Modifications to the Planned Approach During the Course of the Project

There were no significant changes to the planned approach for this project.

Lessons Learnt for Future Projects

During the execution of the project, several difficulties were encountered and these were resolved using the bestengineering approach possible.

Below is a list of key takeaways that could have been anticipated at earlier stages:
1.1.1 Understanding of analysis platform's limitations at the onset of the project
The suitability either of PSCAD, RSCAD and RTDS, stand-alone or in combination with OPAL-RT 6500 and/or MATLAB/Simulink could have been examined to find the best alternative.
The limitations experienced were as follows;

· Lack of tap changer in transformer models in MATLAB/Simulink.
· Lack of frequency dependency modelling for most of the power network elements in MATLAB/Simulink.
· Inadequacy of the emulator OPAL-RT 6500 in accommodating small integration time-steps.
· Capability of the emulator OPAL-RT 6500 to accommodate only a very small network model.
· Observation of numerical stability issues with the time domain solvers in both MATLAB/Simulink and OPAL-RT
6500.
· The need to introduce a 'magic' resistor to the model both in MATLAB/Simulink and HIL simulations (howeverit should be noted that the effect of this is negligible on study results and is a common approach employed innumerical integration studies).
1.1.2 Knowledge of time samplings on measured data needs to be known or planned in advance ofstarting the project execution.
· The input data utilised for models based on SCADA and temporary Power Quality (PQ) monitors were observed to be in significantly different time resolution.
· The time resolution of measured data was not suitable for the discrete time-steps in the real-time simulator.
· The observation of the overall simulation was computationally intensive. This type of difficulty would be seen in other electromagnetic transient analysis environments also with the main driver being the time step and the overall duration of the simulation time. The largest time step that can be used is dictated by the model characteristics and not much can be done about it. The duration of the simulation is split into multiple parts so
that simulation time is shortened, and the data generated can be handled easily.
1.1.3 Control algorithm improvements that improved the performance
· Replacement of the low pass filter with a better performing notch filter to avoid oscillations in harmonic reference signal.
· Introduction of an automatic gain such that the inverter is not overloaded under high irradiance conditions.
· Separation of gain from applying to a single harmonic to a grouping of harmonics thus providing balanced compensation between harmonic orders.
· Introduction of a Proportional Resonant (PR) controller instead of a Proportional Integral (PI) controller while generating harmonics for injection.
· Introduction of additional filtering to cater for unbalanced conditions in the harmonics.
A final point to make regarding learnings relate to observations during the execution of the project.
· Whilst an optimum location of feedback measurement was established for normal operation, it is possible to have multiple measurement points with the possibility to modify them, depending on system operating conditions or other events (for example, faults on a feeder).

· The inverters have an impact on the equivalent network impedance, in particular at the frequencies of current injection, due to a combination of inverter output filter and control loops.

Note: The following sections are only required for those projects which have been completed since 1st April 2013, or since the previous Project Progress information was reported.

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.
Work Package 1 Outcomes
· Literature review – This literature review was delivered as a report and addressed how distributionconnected 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 report3. 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.

Work Package 2 Outcomes
· Work Package 2 report – This report4 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 report5 and expresses the Work Package 3 Outcomes
· Work Package 3 report – The Work Package 3 report6 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. 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.
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.
Post Project Activities
· Technical Summary of Harmonic Mitigation report7 – This work was completed by PSC and provided a high-level summary of all the work undertaken throughout the duration of the project.
· WPD Closedown report8 – This work was completed by WPD and provided an overview of the projects' activities through a project management lens.
The full learning has been disseminated via WPDs Innovation website page where access to full work package reports and both closedown reports is freely available at: www.westernpower.co.uk/Harmonic-Mitigation

Data Access

No data has been generated from the project. The only data used has been collected from WPD's systems.

Foreground IPR

The foreground IPR generated from the project can be seen below.
· Control algorithms

· Work package reports

Planned Implementation

The project has been very successful as all objectives have been fulfilled. However, based on the learning points and the observation during the execution of the project, it was possible to identify future work items that will bring more engineering and scientific knowledge to the existing level of understanding. Various opportunities for further work can be listed as:

· 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. But 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 simulations followed by HIL testing have shown that the developed algorithm can provide a reduction of harmonic distortion in the network. It is highly recommended to work closely with PV farm developers to gather more data on the PV farms, and specifically the collector system and the inverter physical configuration and output filters. This will allow testing the algorithm on models that are closer to the real-time operating conditions. 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

Other Comments

N/A

Standards Documents

N/A