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Technical Report TA User Project

Ensto Hardware in the Loop Testing of Phase Rebalancing Impact

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Abbreviations

DER	Distributed Energy Resource
LV	Low Voltage
LVUR	Line Voltage Unbalance Rate
MV	Medium Voltage
PB	Phase Balancer
Plt	Long Term Flicker Index
PNDC	Power Network Demonstration Centre
Pst	Short Time Flicker Index
PV	Photovoltaic
PVUR	Phase Voltage Unbalance Rate
RTDS	Real Time Simulator
TA	Trans-national Access
THD	Total Harmonic Distortion
VUF	Voltage Unbalance factor

Executive Summary

This project has used the Ensto phase balancer (PB50A-3P-200ADV) for a holistic system testing approach of phase rebalancing. Ensto Phase Balancer is designed to fix unbalanced load in low voltage distribution networks and reduce possible unwanted neutral wire current. This project has evaluated the impact of the Ensto product on the power system, specifically the impact on: phase imbalance, voltage Total Harmonic Distortion (THD), and voltage flicker. To achieve the proposed system testing approach, the power system was evaluated both with and without the Ensto product connected. The effectiveness of the Ensto solution on the system level response was evaluated under different network line impedances and for different levels of phase imbalance (implemented by load and generation imbalance).

This project has utilised a PHIL platform (RTDS and Triphase) to emulate a larger simulated network connected to the PNDCs real LV (400V) network. The results from the testing have shown that the phase balancer operates as expected to balance the phases when the 3 phase load is imbalanced. The results also suggest the Triphase system may have operated erroneously during the phase imbalance testing. This finding will help develop the capability of the Triphase system for use in future phase imbalance studies when operating in 4 wire mode.

1 Project Summary

Power quality is an important issue for Distribution Network Operators (DNOs). DNOs must comply with minimum power quality standards (European and International) when providing an electrical supply to customers. EN 50160 is the European standard that defines voltage parameters for electrical supply in public distribution systems (Low Voltage and Medium Voltage). It should be noted that European utility companies often have additional rules for electricity supply that supplement the requirements specified in EN 50160. The EN 50160 standard specifies that in public distribution systems voltage should remain ±10% for 95% of the week, mean 10 minutes rms. values.

Phase balancing can be an important operational requirement in three phase power systems. If loads are not balanced equally between the three phases it will cause phase imbalance. This will result in: current flow in the neutral wire (potentially leading to overheating of the neutral conductor); voltage phase imbalance (causes higher electrical loses); reduced transformer efficiency (core losses); and transformer degradation (due to windings overheating).

This project has used the Ensto phase balancer (PB50A-3P-200ADV) for a holistic system testing approach of phase rebalancing. Ensto Phase Balancer is designed to fix unbalanced load in low voltage distribution networks and reduce possible unwanted neutral wire current. This project has evaluate the impact of the Ensto product on the power system, specifically the impact on: phase imbalance, voltage Total Harmonic Distortion (THD), and voltage flicker. To achieve the proposed system testing approach, the power system was evaluated both with and without the Ensto product connected. The effectiveness of the Ensto solution on the system level response was evaluated under different line impedances and for different levels of phase imbalance (implemented by load and generation imbalance).

This project has utilised a PHIL platform (RTDS and Triphase) to emulate a larger simulated network connected to the PNDCs real LV (400V) network. This real time platform:

- Enabled the fault level of the simulated network to be controlled;
- Simulated loads and generation to be controlled to vary the level of phase imbalance.

To supplement the simulated network, additional real hardware was connected to the test grid:

- Renewable energy in the form of single phase PV emulators and PV inverters was connected to the PNDC LV network. The addition of single phase generation increased phase imbalance on the test grid.
- One Ensto phase balancer was connected to the test network, to evaluate the impact on voltage THD, and Flicker (short and long time flicker index).

The Ensto phase balancer is shown in Figure 1, the phase balancer can monitor the power quality and power consumption on the connected network. By adjusting the coils in the phase balancer, the current flow can be shifted from a heavily loaded phase to a lightly loaded phase when network imbalance is detected. The Ensto is modular and if interfaced to a SCADA system can be configured remotely.

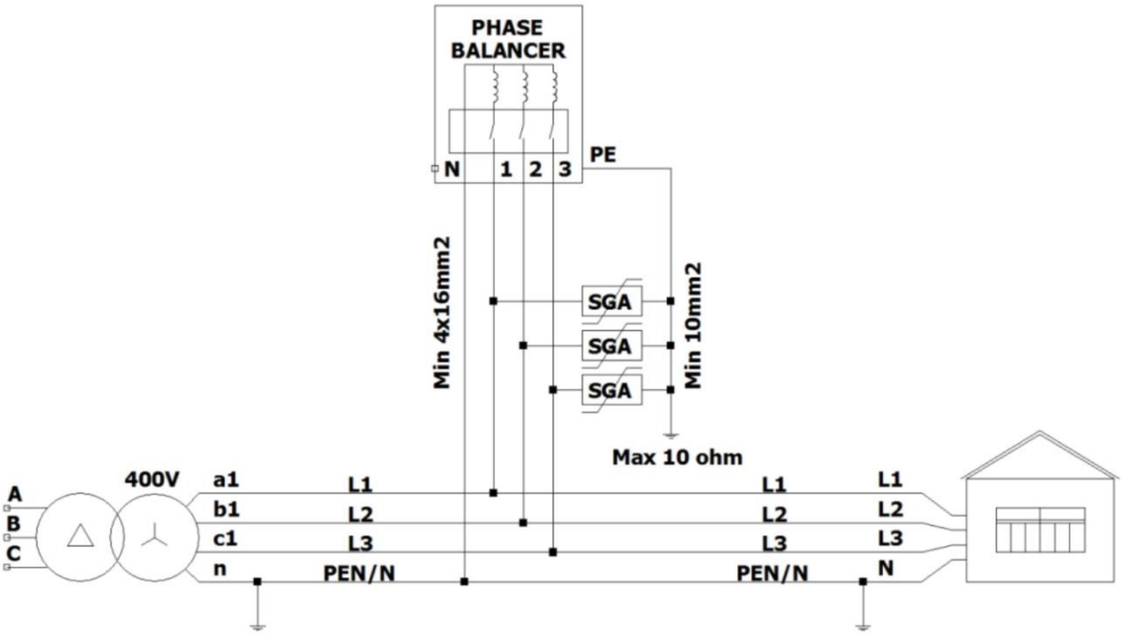

Figure 1: Ensto Phase Balancer connection to LV Network

Project Description

1.1 Objectives

The **objective** of this project is to evaluate how the power system behaves with and without the Ensto phase balancing equipment installed and operating. This project has utilised a holistic system testing approach to evaluate how different variables impact the phase imbalance impact. Specifically the control variables will be:

- The utilization of the Ensto phase balancing equipment: Evaluating the phase imbalance with and without the system connected
- Strength of the grid (fault level of grid infeed): Evaluating the phase rebalancing scheme effectiveness with different grid infeed fault levels
- Load and renewable generation (within simulation and real hardware): Evaluating the phase rebalancing scheme effectiveness with different levels of imbalance (caused by load and generation)

This system testing approach was facilitated by utilizing the PNDC Power Hardware in the Loop platform, existing load, existing renewable generation and Triphase Programmable Power Converter interface. The test configuration is described in a later section.

The outcome of this project is a detailed understanding of the effectiveness of the load balancing strategy on power system imbalance for varying levels of grid strength, load, and renewable generation. Measurement variables that were measured and analysed in this project include:

- Neutral current – Current flow in the neutral indicates load imbalance on the phases. This leads to voltage drops and overheating of the neutral conductor.
- Voltage unbalance, phase shift correction – In balanced distribution networks all three phase voltages are 120 degrees apart. In balanced networks only the positive sequence exists. In unbalanced loads negative and zero sequence voltages are also present. Specifically these parameters will consider: %PVUR (deviation from phase voltage), %LVUR (deviation from line voltage) and %VUF (ratio of negative to positive sequence voltage).
- Power losses – Phase imbalance will result in power losses in the network, this will be calculated as part of this study. This will include losses associated with Transformer efficiency.
- Flicker – Logging the short and long term flicker (Pst/Plt) associated with the phase imbalance scheme operational and non-operational.

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1.2 Test Plan

In this section the test objectives are defined, and the test cases and the setting parameters for testing the Ensto Phase Balancer at the Power Network Demonstration Centre are summarised.

1.2.1 Device under test

The device under test is the Ensto Phase Balancer PB50A-3P-200ADV. The Ensto Phase Balancer is a device that aims to fix unbalance problems in low voltage distribution grids. The unit is designed to be installed parallel with distribution grids where the unbalance problem exists. The Ensto Phase Balancer is designed to correct asymmetric load problem, increase short circuit current and decrease harmonic content in low voltage networks. The advanced version offers extra features e.g. grid integrity monitoring, overload protection (hardware/software)and operation indicators and RS232 for remote control application option for communication. The benefits the system provides include:

- Corrects unbalanced three phase load
- Maximizes line capacity and decreases line losses
- Reduces total harmonic distortion (THD)

A line diagram and a picture of the Ensto Phase Balancer PB50A-3P-200ADV is shown in Figure 2.

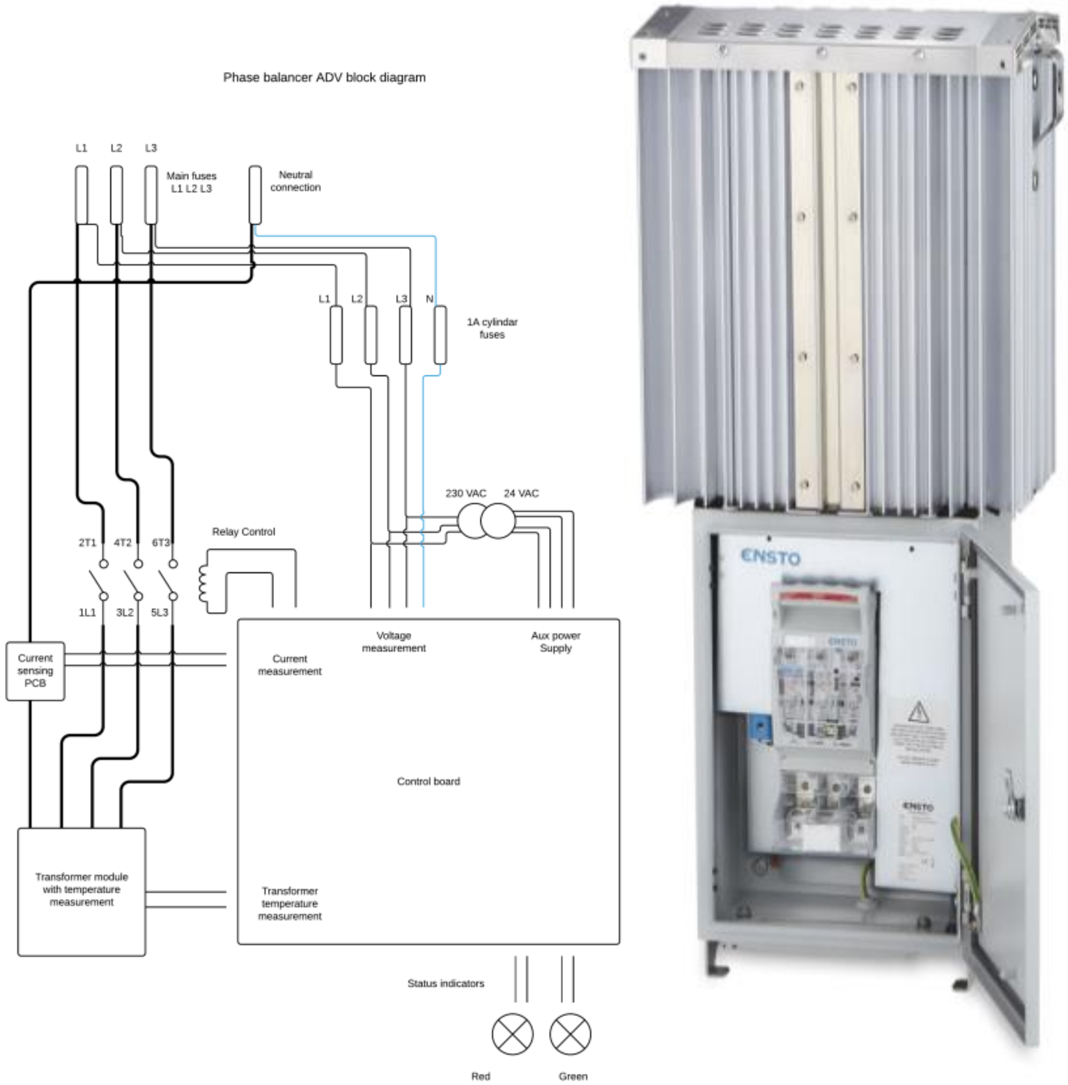

Figure 2: Line diagram and picture of ENSTO phase balancer

1.2.2 PNDC Test Set-up

The User Group (in this case Ensto) provided the Phase Balancer product for the purposes of this test. The rest of the equipment, as specified in Figure 3, was provided by PNDC. A high level experimental specification line diagram for testing in this project is shown below. The key TA infrastructure components are:

1. The RTDS (real time simulator)
2. The Triphase programmable power converter (interface from simulation to electrical network)
3. An LV (400V) network
4. 400V loadbanks
5. PV panels and associated inverters (or equivalent PV emulators) Ensto Phase Balancer

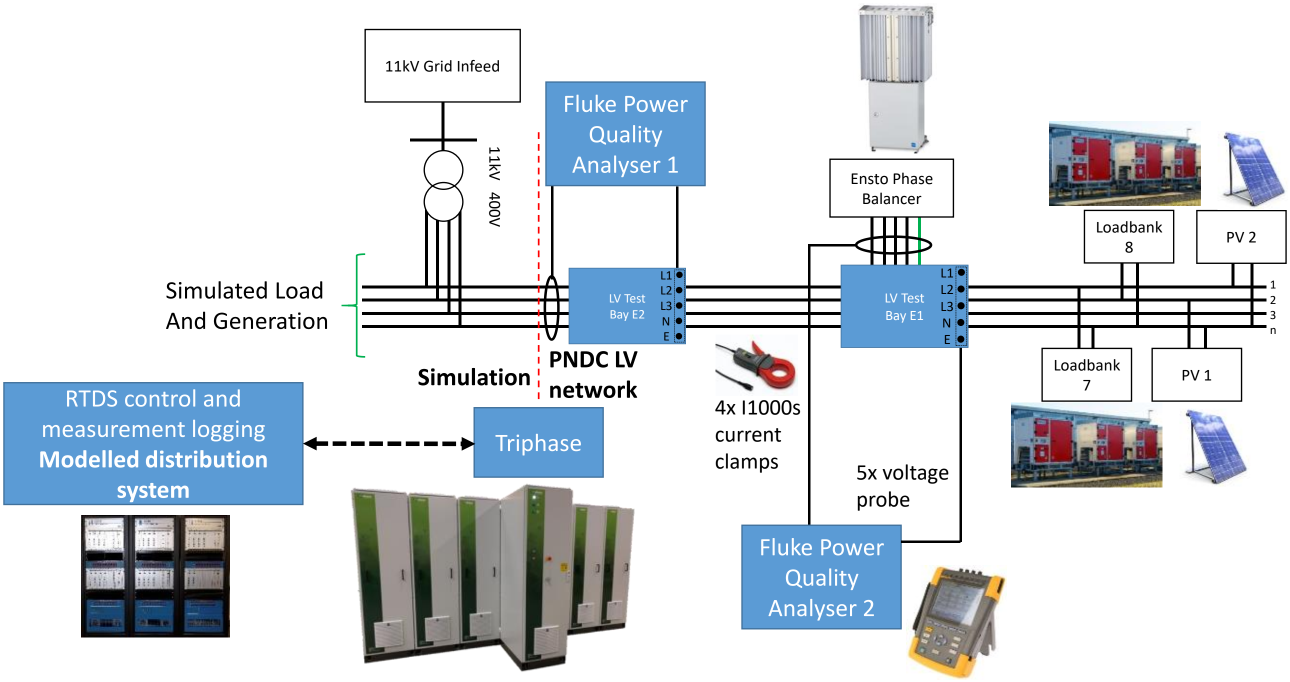

Figure 3: PNDC test configuration

1.2.3 Recorded test data

In each of the test scenarios the following parameters were recorded using the Fluke Power Quality Analysers shown in Figure 3.

- Voltage phase-neutral
- Voltage phase-phase
- Neutral current
- Total Harmonic Distortion Voltage
- Voltage harmonics
- Flicker

On completion of the testing all of the recorded data was provided to ENSTO for analysis.

1.3 Voltage

By monitoring the phase-neutral and phase-phase voltages the voltage unbalance was calculated.

In balanced distribution networks all three phase voltages are 120 degrees apart. In balanced networks only the positive sequence exists. In unbalanced loads negative and zero sequence voltages are also present. Specifically these parameters were considered: %PVUR (deviation from phase voltage), %LVUR (deviation from line voltage) and %VUF (ratio of negative to positive sequence voltage).

1.4 Neutral current

Current flow in the neutral indicates load imbalance on the phases. This leads to voltage drops and overheating of the neutral conductor. By monitoring the Neutral Current the magnitude of load imbalance can be quantified.

1.5 Power losses

Phase imbalance will result in power losses in the network, this was calculated as part of this study. This will include losses associated with Transformer efficiency.

1.6 Total Harmonic Distortion Voltage & Voltage Harmonics

One of the advantages that the Ensto Phase Balancer is a reduction in Voltage Harmonics on the network [1]. The voltage harmonics were monitored during periods of operation with the Ensto active and inactive to determine the Phase Balancer impact on network voltage harmonics.

1.7 Flicker

One of the advantages that the Ensto Phase Balancer is a reduction in Flicker on the network [1]. The flicker was monitored during periods of operation with the Ensto active and also inactive to determine the Phase Balancer impact on network Flicker. Both the short and long term flicker (Pst/Plt) associated with the phase imbalance scheme operational and non-operational were recorded.

The calculation period of the short term flicker index (P_{st}) was over 10 minute intervals and the calculation period for long term flicker index (P_{lt}) was over two hours periods.

1.7.1 Test Scenarios

A number of tests were conducted to emulate different network conditions. A variable resistive load was connected to phase one of the three phase network in all of the tests. In the even numbered tests, an additional fixed load of 10kW was placed on phase two. On the tests numbered 4*n and 4*n-1, where n = 1,2,3… 5kW of PV generation was connected to phase three.

Tests 1-16 establish a reference without the DUT connected and in tests 17-32 the DUT was connected. The test cases are summarised in Table 1.

Table 1 Summary of test scenarios

Test no.	Ensto Phase Balancer	OHL equivalent length	Loadbank	5 kW PV-generation	10 kW fixed R-load
1	OFF	0.01km	Script	OFF	OFF
2	OFF	0.01km	Script	OFF	ON
3	OFF	0.01km	Script	ON	OFF
4	OFF	0.01km	Script	ON	ON
5	OFF	0.3km	Script	OFF	OFF
6	OFF	0.3km	Script	OFF	ON
7	OFF	0.3km	Script	ON	OFF
8	OFF	0.3km	Script	ON	ON
9	OFF	0.6km	Script	OFF	OFF
10	OFF	0.6km	Script	OFF	ON
11	OFF	0.6km	Script	ON	OFF
12	OFF	0.6km	Script	ON	ON
13	OFF	1km	Script	OFF	OFF
14	OFF	1km	Script	OFF	ON
15	OFF	1km	Script	ON	OFF
16	OFF	1km	Script	ON	ON
17	ON	0.01km	Script	OFF	OFF
18	ON	0.01km	Script	OFF	ON
19	ON	0.01km	Script	ON	OFF
20	ON	0.01km	Script	ON	ON
21	ON	0.3km	Script	OFF	OFF
22	ON	0.3km	Script	OFF	ON
23	ON	0.3km	Script	ON	OFF
24	ON	0.3km	Script	ON	ON
25	ON	0.6km	Script	OFF	OFF
26	ON	0.6km	Script	OFF	ON
27	ON	0.6km	Script	ON	OFF
28	ON	0.6km	Script	ON	ON
29	ON	1km	Script	OFF	OFF
30	ON	1km	Script	OFF	ON
31	ON	1km	Script	ON	OFF
32	ON	1km	Script	ON	ON

2 Results and Conclusions

This section presents the results from the testing and draws some conclusions from the observed response.

2.1 Results from testing

Fluke logging was setup at the terminals of the Triphase system and at the terminals of the ENSTO phase balancer, as shown in Figure 3. The RMS voltage and current profiles at the Triphase terminal for test 05 are shown in Figure 4 and Figure 5. In this test the feeder simulated length is 0.3km, there is a single phase load on phase 1 and no load or generation on phase 2, or phase 3. On post-test analysis of the results it was observed that a possible erroneous response from the Triphase during the test. As the phase 1 load is increased the current in phase 1 and the neutral also increases. Simultaneously the voltage on phases 1 and 3 increase and the voltage on phase 2 increases. The neutral also increases, shown on the secondary y-axis, however this increase is negligible in comparison to phase 2. To determine if this response was correct the test was repeated in simulation in isolation as discussed in section 2.2

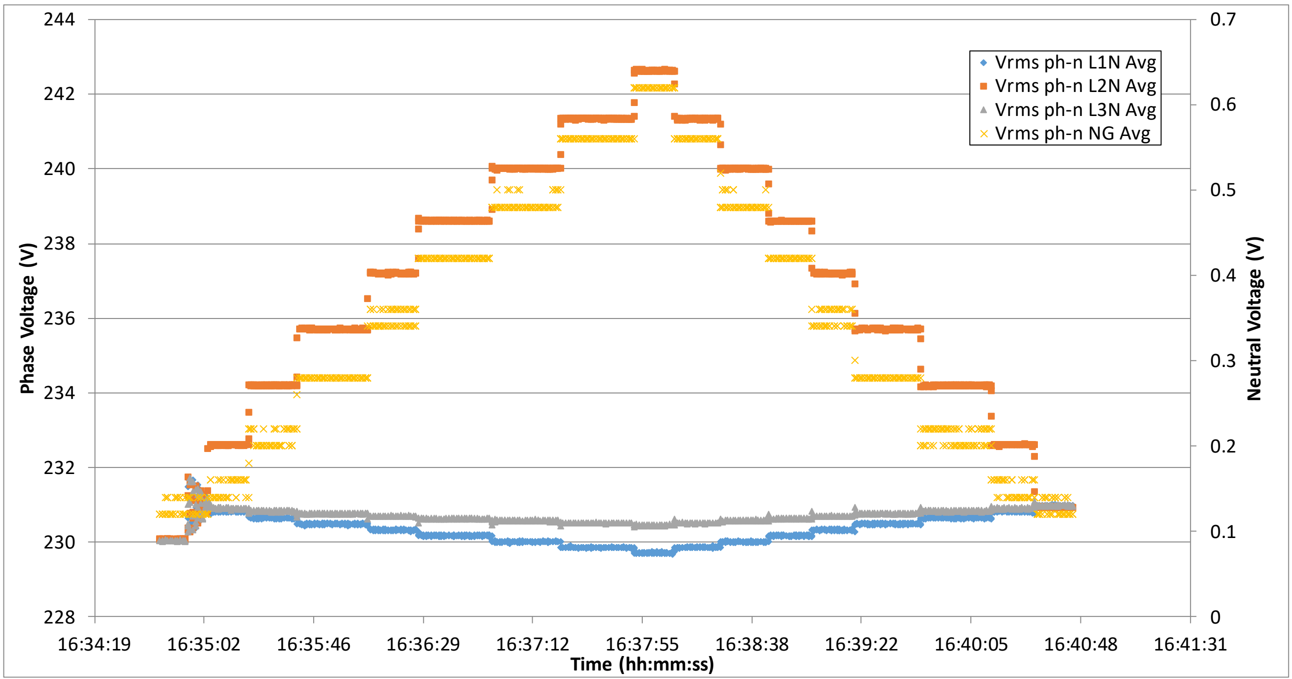

Figure 4: Test 05 Voltage profiles

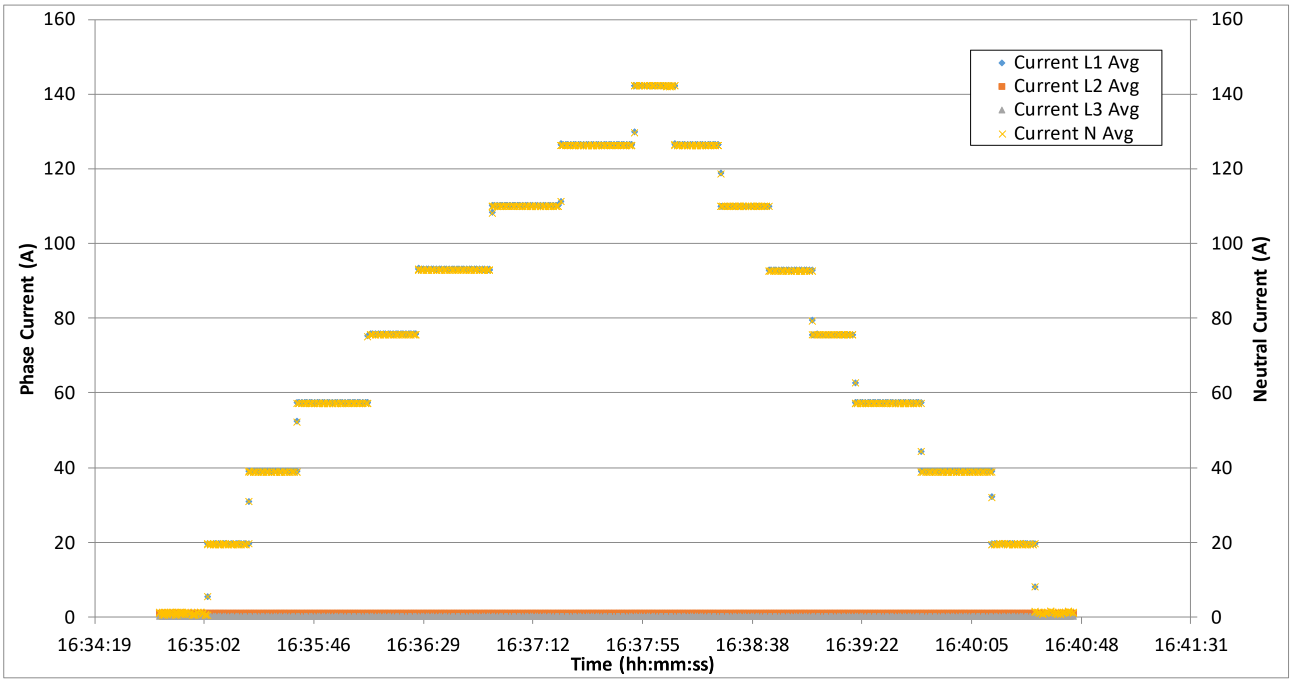

Figure 5: Test 05 Current profiles

2.2 RTDS simulation

The test setup (including the single phase load) was repeated in the real time simulator to determine if the response observed in section 2.1 is correct. The response in simulation is shown in Figure 6 and Figure 7. This response differs from the response observed during testing in that when the load is applied the unloaded phases (labelled N301 and N300) in the figures remain constant when the single phase load is applied. This suggests that the response recorded from the test may be incorrect. Possible causes of this error may be in how the Triphase system was configured for this specific load imbalance test. It is suggested that the test should be repeated in a later study to understand the discrepancy between the simulation and Triphase response.

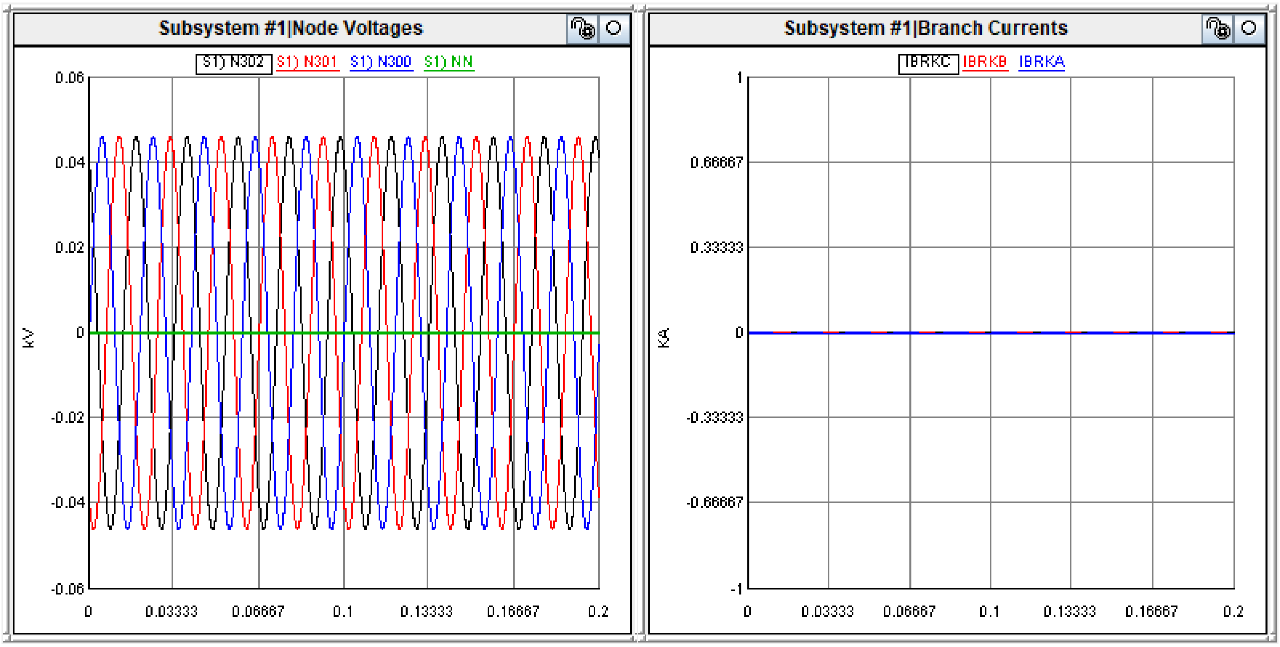

Figure 6: With no single phase load

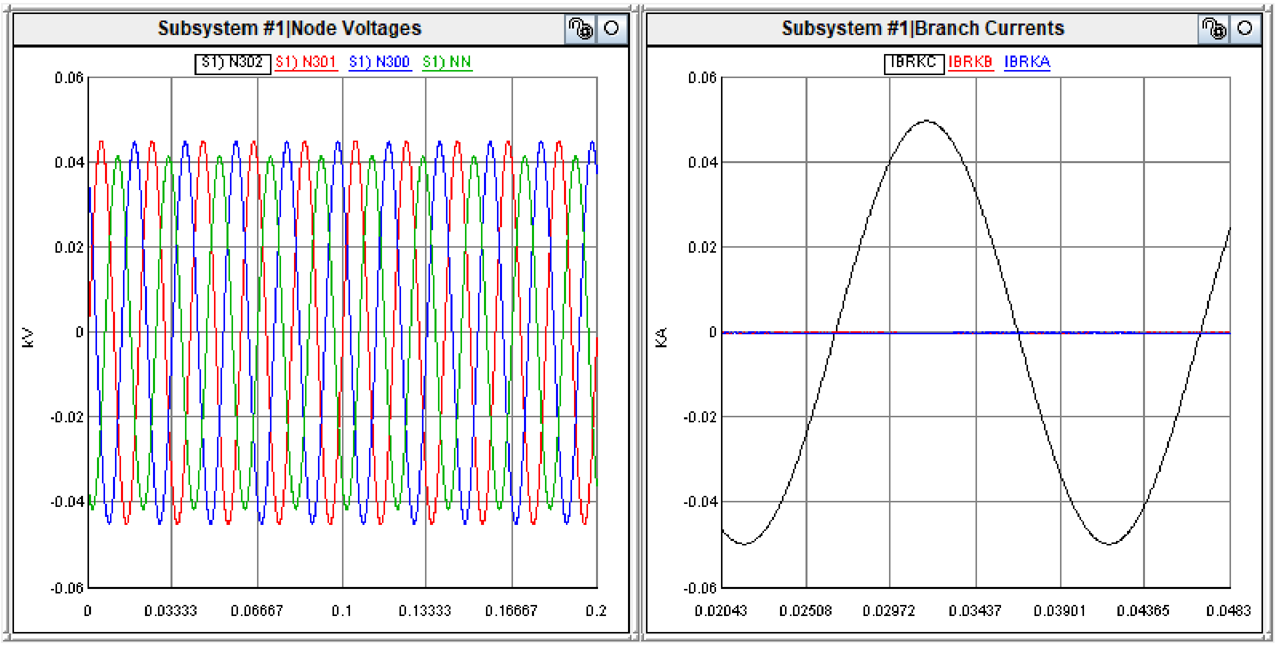

Figure 7: With single phase load

2.3 ENSTO response during testing

Test 5 reported in section 2.1 was repeated with the ENSTO phase balancer connected (test 21 in Table 1) and the response is shown in Figure 8 and Figure 9. It can be observed that the phase balancer attempts to reduce the voltage imbalance by injecting current in the unloaded phases. This has a corresponding impact on the phase voltage. This test was repeated at a range of simulated line impedances and the same response was observed in all cases. The total harmonic distortion and flicker were not impacted by the response of the phase balancer during testing.

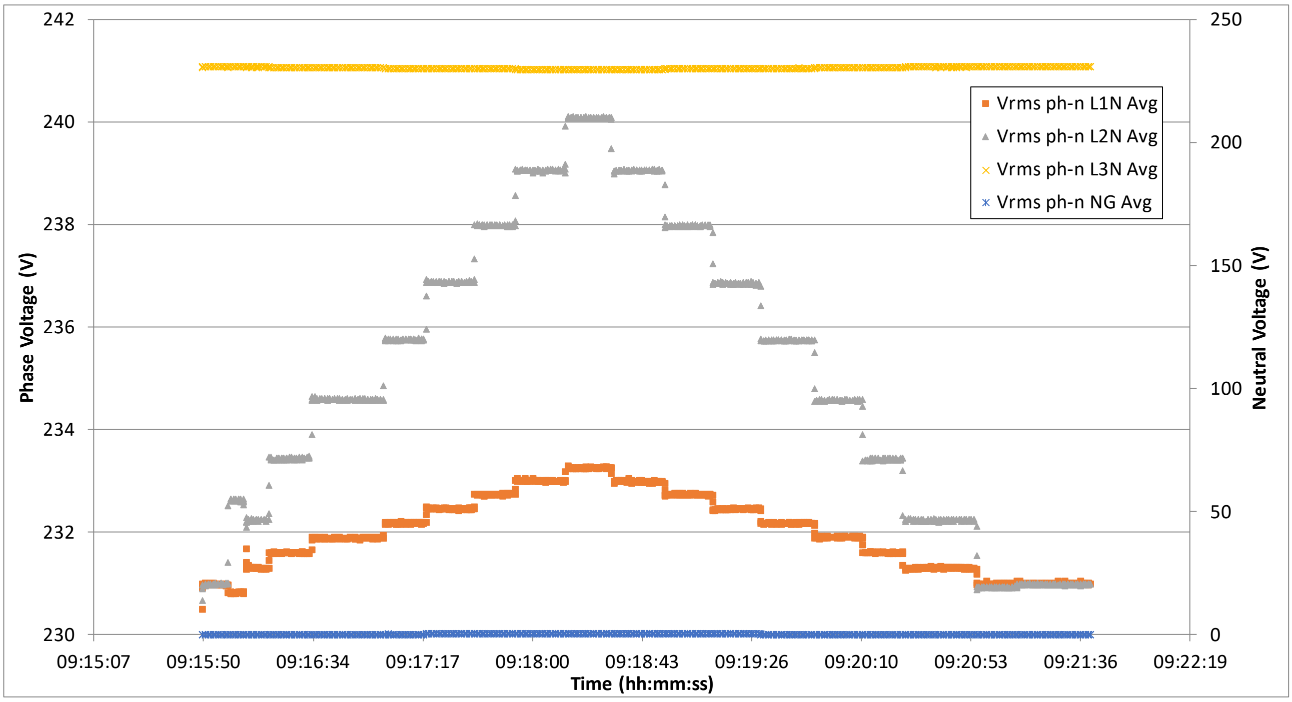

Figure 8: Test 21 voltage profiles

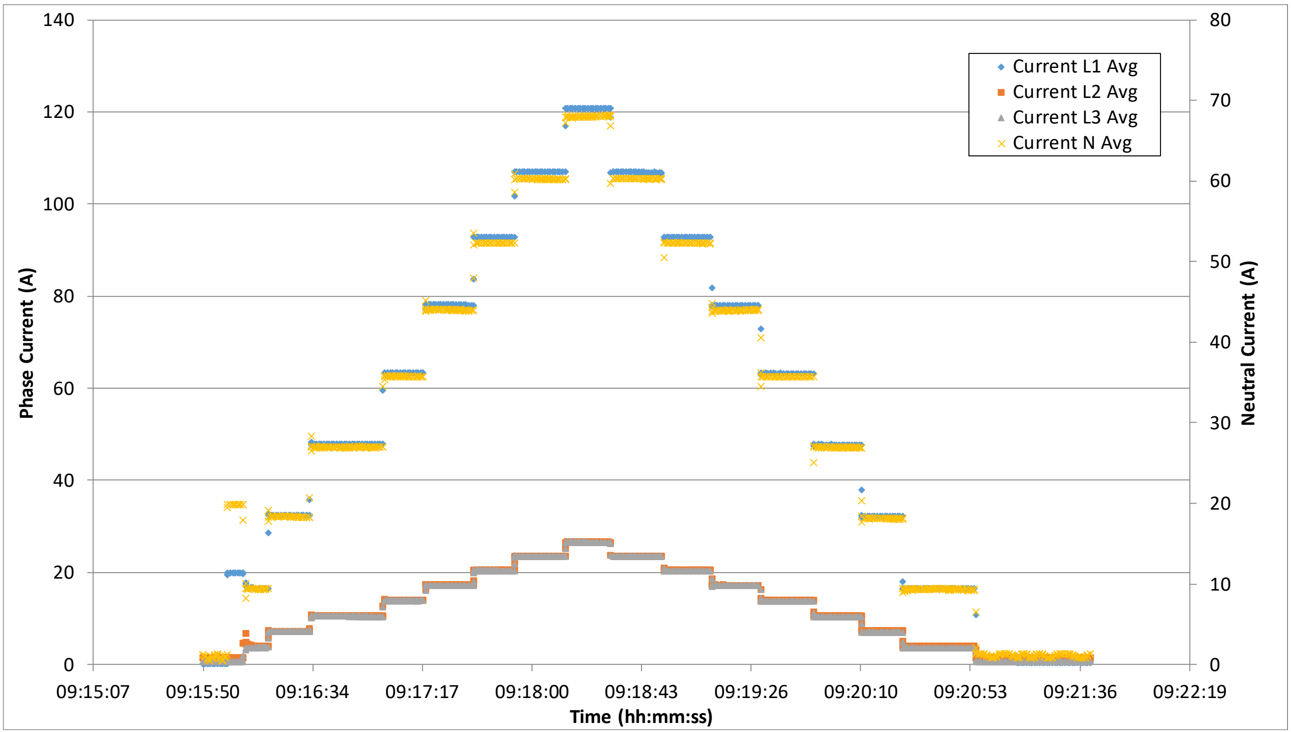

Figure 9: Test 21 current profiles

2.4 PV-production

The results for tests 11 and 27 are presented in Figure 10. This figure presents the results form a situation with no load present, 5kW of generation, around 300 watts are lost in cables and connections, and 4.7kW is transferred upstream. The results indicate that the power transferred by phase 3, to which the generator is connected, is reduced by 21% from 4.7 kW to 3.7kW when the phase balancer is operational.

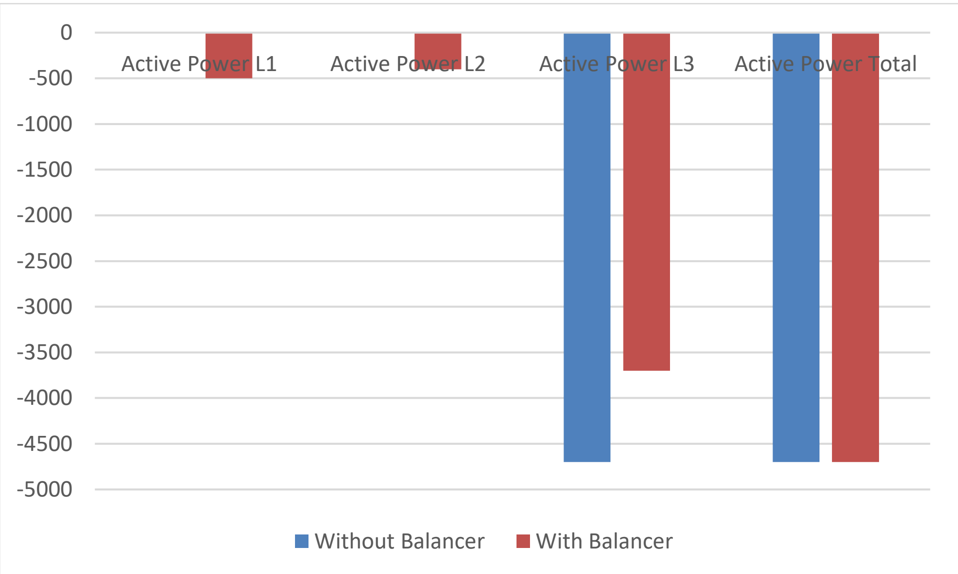

Figure 10: Phase power with 5kW distributed generation on phase L3

3 Open Issues and Suggestions for Improvements

The test facilities at PNDC are of a very high standard. There was one issue in the measurement setup of the Phase balancer. The problem was the location of the earthing point of the neutral conductor. In a normal LV network, the neutral conductor is earthed at the distribution transformer, at the connection point of the customer, and in between, should the feeder length require earthing. In the test setup, however, the neutral was only earthed at the "customer" load connection point. This makes the results of the test somewhat unconventional. Test 13 is provided as an example in the following explanation.

The measurements are made at the output of the grid simulator, and thus show negligible voltage change on the neutral with respect to earth regardless of the neutral current, since the measurements are made at the (only) earthing point of the neutral conductor.

The grid simulator was configured to generate a voltage on the neutral that was proportional to the current flowing in the neutral conductor, which resulted in the neutral voltage drifting away from earth at the simulated distribution transformer connection point as load increased. This can be seen in the results as an increase on the voltage of phase L2 with respect to neutral at the customer connection point, where the neutral is earthed. The line-to-neutral voltage on phase L2 at the connection point is equal to the sum of the generated line voltage L2 and the neutral-to-earth voltage at the generator. Since the neutral current is in phase with the L1 voltage and the feeder was configured in the grid simulator to have significant inductive reactance, the voltage drop on the virtual neutral feeder is lagging the voltage on L1, being more aligned with the voltage on L2, but with opposite polarity. The phase voltages measured during Test 13 presented as a function of total load are presented in Figure 11.

It is proposed that the testing be repeated with the proposed alternative arrangement of the Tri-phase system. This may help with the erroneous response discussed in section Results from testing.

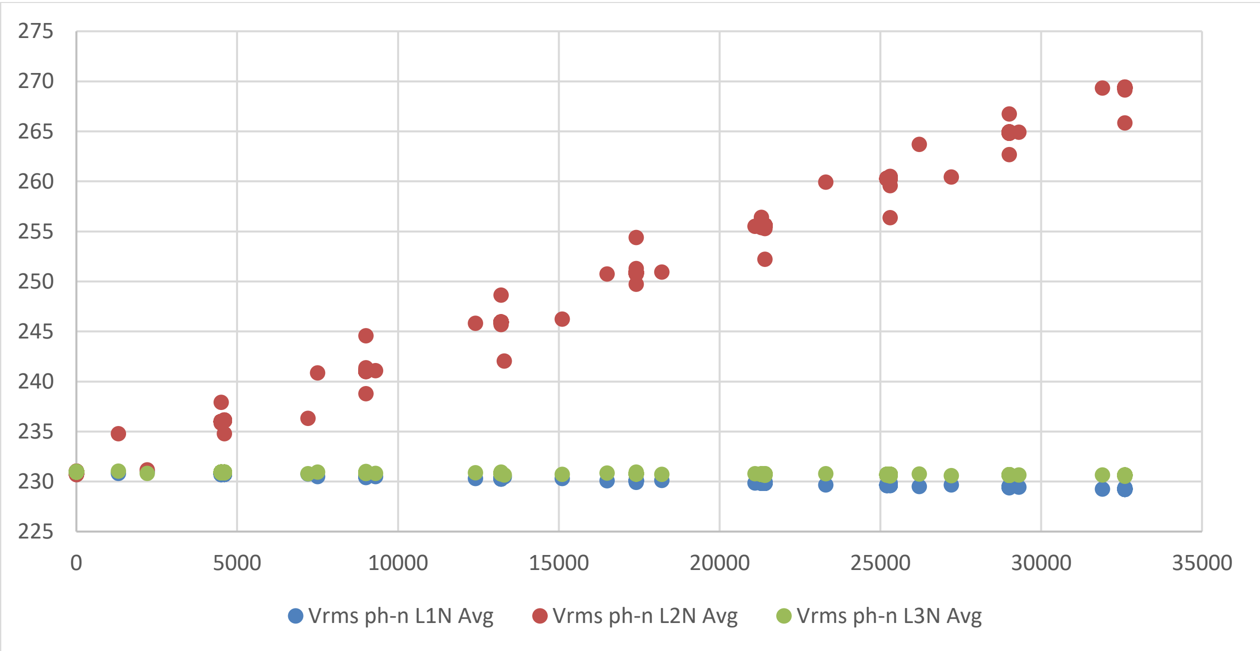

Figure 11: Test 13, Line-to-Neutral voltages as function of load on L1 without DUT

4 Conclusions

This testing has shown that the ENSTO phase balancer operates as expected to attempt to re-balance the phases. The phase balancer injects current into the unloaded phases in attempt to rebalance the loading. This testing has also indicated a possible erroneous configuration of the Triphase system for 4 wire-phase imbalance operation. It is proposed based on the findings from this test that further investigation is required to identify the cause of the response observed during testing.

5 Dissemination Planning

The testing results were presented to the main UK distribution Network Operators (e.g. UK Power networks, Scottish Power Energy Network, Scottish & Southern Energy Network). There were also presented at the EA technology PLANTX 2018. Conference (EA Technology Chester Racecourse, Chester CHI12LY 6th June 2018).

References

1. LAFORTUNE, M., D. BOUCHARD, and J. MORELLI, *Phase Swapping for Distribution System Using Tabu Search.*
2. Sathiskumar, M. and S. Thiruvenkadam, *Phase Balancing of Unbalanced Distribution Network through Hybrid Greedy-Fuzzy Algorithm.* International Journal of Computer Applications, 2011. 34(6).
3. Li, Y. and P.A. Crossley, *Voltage balancing in low-voltage radial feeders using Scott transformers.* Generation, Transmission & Distribution, IET, 2014. 8(8): p. 1489-1498.
4. Civanlar, S., et al., *Distribution feeder reconfiguration for loss reduction.* IEEE Trans. Power Del.;(United States), 1988. 3(3).
5. Peng, Q., Y. Tang, and S.H. Low, *Feeder reconfiguration in distribution networks based on convex relaxation of opf.* IEEE Transactions on Power Systems, 2015. 30(4): p. 1793-1804.
6. Shirvani, M., et al., *Application of on load tap changer for voltage control.* Advances in Natural and Applied Sciences, 2014. 8(6): p. 920-925.
7. Gao, C., *Voltage Control in Distribution Networks using On-Load Tap Changer Transformers*. 2013, University of Bath.
8. Foata, M., C. Rajotte, and A. Jolicoeur, *On-load tap changer reliability and maintenance strategy.* Cigré International Council on large electric Systems, Paris France, 2006. 28.
9. Beharrysingh, S., *Phase unbalance on low-voltage electricity networks and its mitigation using static balancers*. 2014, © Shiva Beharrysingh.
10. Mathad, V.G., B.F. Ronad, and S.H. Jangamshetti, *Review on comparison of FACTS controllers for power system stability enhancement.* International Journal of Scientific and Research Publications, 2013. 3(3): p. 2250-315.
11. Ma, Y., A. Huang, and X. Zhou. *A review of STATCOM on the electric power system*. in *2015 IEEE International Conference on Mechatronics and Automation (ICMA)*. 2015. IEEE.
12. Bhutto, G.M., B. Bak-Jensen, and P. Mahat, *Modeling of the CIGRE low voltage test distribution network and the development of appropriate controllers.* Transactions on Smart Grid and Clean Energy, 2013. 2: p. 184-191.
13. Samuelsson, O., et al. *Active distribution network—demonstration project ADINE*. in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*. 2010. IEEE.
14. Indumathi, R., M. Venkateshkumar, and R. Raghavan. *Integration of D-Statcom based photovoltaic cell power in low voltage power distribution grid*. in *Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on*. 2012. IEEE.
15. Mitra, P., G.K. Venayagamoorthy, and K.A. Corzine, *SmartPark as a Virtual STATCOM.* IEEE Transactions on Smart Grid, 2011. 2(3): p. 445-455.