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Using power factor to limit the impact of energy storage on distribution network voltage

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Abstract

The introduction of embedded renewable generation and energy storage into the electricity grid may result in increased complexity to the Distribution Network Operator (DNO) in managing the voltage within statutory limits. This paper investigates how the voltage at the point of common coupling between the grid and an energy storage system could be adapted such that the charging and discharging of a battery energy storage system has a neutral impact on the voltage at that point. The paper uses measured results from the Willenhall Energy Storage System to show that a “seagull” shape curve of Power and corresponding Var setting could be used to mitigate against voltage rise or fall on the Network caused by the Energy Storage System.

Keywords: Voltage regulation, voltage control, energy storage, distribution networks, power factor

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1. Introduction

Voltage regulation on distribution networks is becoming increasingly more complex due to the rising deployment of distributed generation (DG). Reverse power flows and excessive reactive power cause voltage rise, and can be directly linked to the installation of distributed renewable energy systems (RES), and in particular large concentrations of grid connected photovoltaic (PV systems) [1]. According to [2], PV penetration starts to adversely affect voltage rise when the nominal generation capacity of individual PV system exceeds 2.5kW. In the UK, 37% of domestic PV is rated at 4kW, so a cluster of domestic PV systems on a typical suburban LV distribution network might have a capacity of approximately 500kW. It has been suggested that this could cause voltage rise at the local distribution transformer [3], [4]. These problems are more pronounced at low voltage “weak grid” parts of the distribution network. Voltage fluctuations beyond acceptable limits can cause damage to electrical appliances and machines, failure of fault protection systems and an overall reduction in system reliability and power quality [5]. In addition to inverter connected RES, there is also increasing quantities of battery energy storage systems connected to the grid and these may exacerbate the system as they both import and export power.

Traditional methods of centralised voltage control, such as reactive power consumption by the grids synchronous generators, PF correction capacitors or automatic on-load tap-changers (OLTCs), are important aspects of grid voltage management. However they could lack the flexibility and rapid response needed to cope with voltage variations caused by fast acting inverter connected power plant. OLTCs are more expensive to install or retrofit than offload tap changers [6] and it is not desirable to replace all of these in the LV Network to help improve control. Since many centralised synchronous generators are now being switched off to meet carbon reductions targets, the UK National Grid has outlined the increasing need for greater dynamic reactive power absorption and generation at the distribution level [7].

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Voltage rise can be relieved through a combination of setting the DG RES or battery inverter to curtail some active power injection onto the grid, along with some reactive power absorption. However, this reduces the operational capacity factor of the plant, ultimately decreasing its capacity to produce active power. Reducing the opportunity for generators/energy storage to maximize earnings from their power purchase agreements (PPA) with electricity suppliers. This opportunity cost also contributes to a general increase in levelised cost of electricity (LCOE) over the operating lifetime.

Reactive power control (RPC) of inverters is one approach which has shown to be effective in mitigating these voltage fluctuations [8]. Despite the fact that dynamic RPC is well known as a method of mitigating voltage rise, there is little incentive to implement it since; commercial and industrial customers prefer not to pay for the absorption of reactive power whether they are a generator or a consumer; and domestic customers are not required to pay for any reactive power consumption at all, neither can they sell their reactive power if they have domestic PV, since reactive power is not traded on LV 400V network. As a result, domestic PV inverters, BESS and commercial DG RES inverters usually operate at unity power factor (PF) [8].

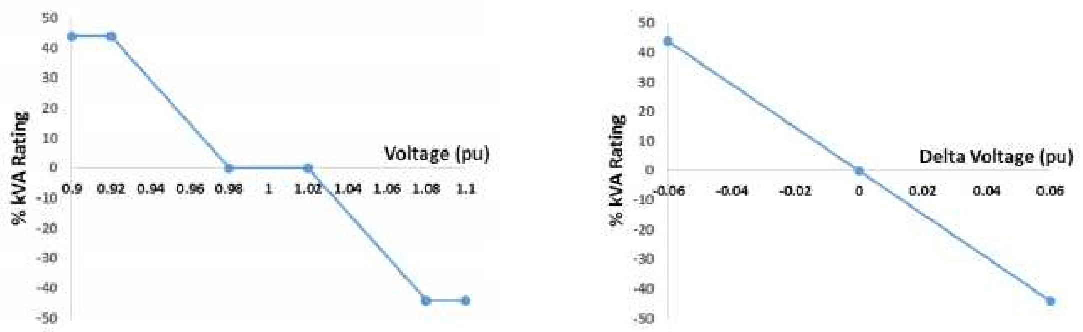
Consequently, this lack of RPC on distribution networks means not only is there difficulty in quantifying the effects of large volumes of RPC on voltage rise in a DG setting, but also that developing new technologies and system innovations is a slower and more challenging process. All the while, demand for power and increasing installation of DG RES continues to compound the challenges of voltage rise. If the inverter connected plant can be made to look voltage neutral at the point of common coupling, this would allow traditional reactive power control to be used as normal. As the impact of each inverter connected plant is not visible to the Network and its control strategy may operate in different time scales – a closed loop control system which adjusts Reactive Power based on voltage at the PCC is not necessarily the best method of maintaining a stable grid. An open loop control method is suggested as a more stable approach where the Reactive Power setting is determined by another means.

Recent research points towards two main methods for RPC and setting the PF of smart inverters; fixed PF control and volt-var droop control (VVC). Fixed PF involves setting the inverter to either absorb or inject reactive power, at a constant PF value. VVC involves a pre-programmed feedback loop, in which the inverter responds to a voltage signal from the point of common coupling, thereby adjusting the PF to determine the reactive power flow. A study by [9] stated that while fixed PF is very effective in shifting the voltage profile up or down, VVC could flatten a variable voltage profile, making it a more precise method for providing secondary voltage support. However, this is difficult to prove.

A report by [10] detailed an investigation into the best VVC setting to be used for PV inverters over a year's worth of different loads and weather conditions. It concluded that VVC settings provide greater benefit during high load and high solar variability conditions, but less benefit during milder load and reduced variability in weather conditions.

Since PV and other RES are inherently variable in power output, a study by [11] assessed the suitability of an IEEE standard 1547 default setting for VVC. The default setting was designed to be applied to any given scenario such as high or low RES penetration; urban or rural; or strong or weak grids. The default setting has a rather benign, non-aggressive (shallow) droop, a large dead band region between 0.98 – 1.02 Vpu and a minimum PF setting of just less than ±0.9. This setting is adequate for providing limited mitigation over a broad range of operating conditions, however, for more extreme voltage scenarios it is ineffective. References [11]and [6] suggested that it be modified to give a steeper droop curve, which does not feature any dead band region as shown in Fig. 1.

While research has focused on inverter based PV systems, there is an increasing prevalence of battery energy storage systems on the electricity grid. If these are left to operate at unity power factor, these would also impact the voltage on the system. The Willenhall ESS in the UK, however, provides a unique and valuable platform for investigation since this ESS was specifically commissioned to test the feasibility of battery storage for grid support [12]. Unlike a cluster of typical domestic PV system inverters, Willenhall ESS inverter can be programmed to inject or absorb 2MW of reactive or real power onto the distribution network. This quantity of power would be equivalent to approximately 3000 domestic 4kW PV systems, running at 17% efficiency at 12.00 noon on a clear day. Willenhall ESS is positioned close to an 11kW feeder and that has a fault level of 250MVA.



(a) (b)

Fig. 1.Volt-var setting suggested by IEEE 1547 sub group (a) and a suggested adaptation of this (b) [11]

The aim of this paper is to provide a practical investigation into the optimal power factor settings of DG RES inverters for mitigating voltage rise on medium and low voltage distribution networks by using the Willenhall Energy Storage System to determine what settings would be required to maintain the voltage at the point of common coupling (PCC) at close to a fixed value regardless of the change in Power. Section 2 introduces the Willenhall Energy Storage System. Section 3 looks at the process of determining the settings and checking for a voltage neutral condition. Section 4 looks at modelling the results from Section 3 and compares the likely grid impacts to other methods of voltage control for this system. Section 4 is a conclusion to this work that suggests an alternative to the fixed PF control and volt-var droop control.

2. Experimental Platform

The Willenhall Energy Storage System (WESS) is a collaborative research facility, funded by the EPSRC under the 'Capital for great technologies call'. The full-scale system includes a 2MW, 1MWhr Toshiba lithium-titanate battery system [12], which is interfaced to a 2 MVA ABB inverter, connected to the grid through an 11 kV feed at the Willenhall primary substation, via a step-up isolation transformer. The 11kV and site layout is shown in Fig. 2. While a photo of the site is shown in Fig. 3. The battery system has 21,120 cells with a nominal 2.3V and 20Ah capability.

The system was designed to be a fast-acting energy storage system and is able to transition from full import to full export and vice versa in a sub-cycle time scale. The Power and Vars can be varied separately up to a maximum of just over 2MVA rating with full four quadrant operation.

The voltage measurement used in this paper for the purposes of the study, is the LV voltage at the G59 protection relay. The absolute connected LV busbar voltage is affected by the following varying factors:

- HV system voltage at the primary substation;
- Load on the feeder (both upstream and downstream of the substation)
- Load on the individual secondary substations.

These factors cannot be controlled and are held constant on the public electricity network for the purpose of trials, so it is difficult to fully validate the impact that changes to the Power and Vars has on the system voltage. This complicates the means to look at the impact of the energy storage system on the voltage and is the reason why it is difficult to validate volt-var control on a network.

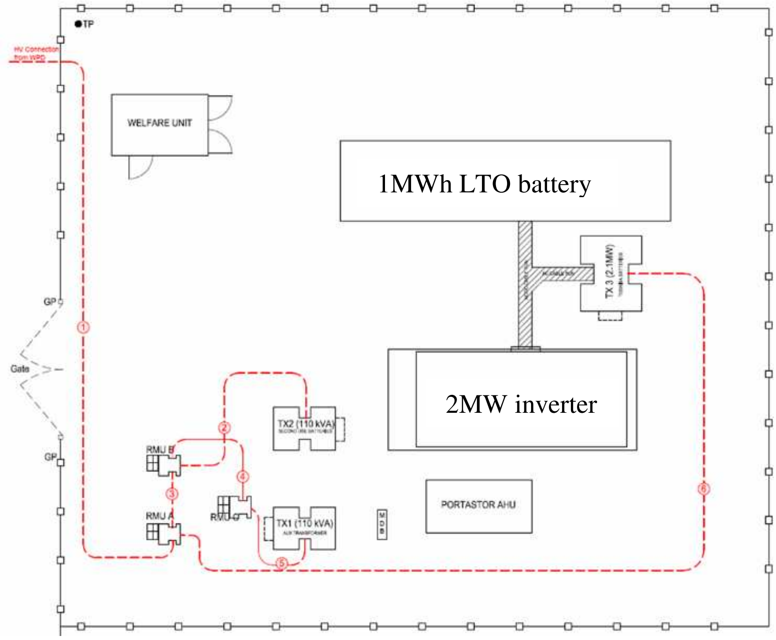


Fig. 2. Site layout – showing 11kV cabling

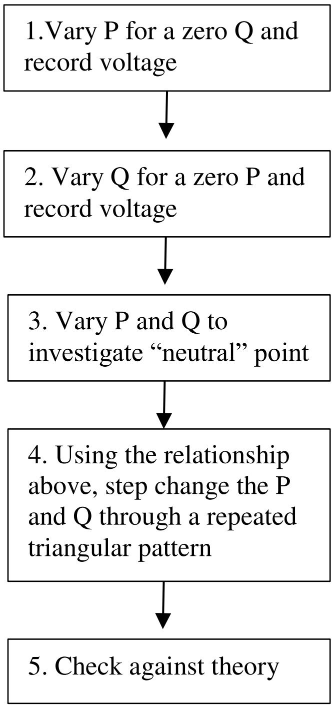
Fig. 3. Site Photo – showing battery system on the left and the inverter on the right with air handling unit

3. Experimental Measurements

The aim of the paper is to understand what the settings of the battery energy storage system would need to be in order to maintain close to voltage neutral connection across a range of power set points and to compare this to a fixed power factor.

The process in Fig. 4 was used to calculate the power factor that the inverter would need to operate at in order to look voltage neutral at the point of common coupling.

Fig. 5 shows the variation of voltage with a changing Power set point where a negative value represents import and a positive value represents export. There is an approximate linear variation of average recorded voltage across the three phases over a several minute period for different set points.



1.Vary P for a zero Q and record voltage

2. Vary Q for a zero P and record voltage

3. Vary P and Q to investigate "neutral" point

4. Using the relationship above, step change the P and Q through a repeated triangular pattern

5. Check against theory

Fig. 4. Process for determining power factor at different Power set points for voltage neutral conditions

Fig. 6 shows the variation of voltage with changing the Var set point at zero power. There is an approximate linear variation of average recorded voltage across the three phases over a several minute period, which as expected has more influence on the voltage than just varying the power. Using the results from Fig. 5 and Fig. 6 as a starting point, the Vars were varied for a fixed Power set point to try to identify the voltage neutral condition as shown in Fig. 7 for the discharge condition. A similar graph was obtained for the charge condition. The impact of network voltage variation can be seen by the spread of the points and indicate that this is not an accurate process but represents a pragmatic engineering approach at this time. Taking the chosen values, which gave this neutral condition, gives a P/Q lookup curve in Fig. 8. This curve is not the same as a droop curve but has more of a "seagull" shape.

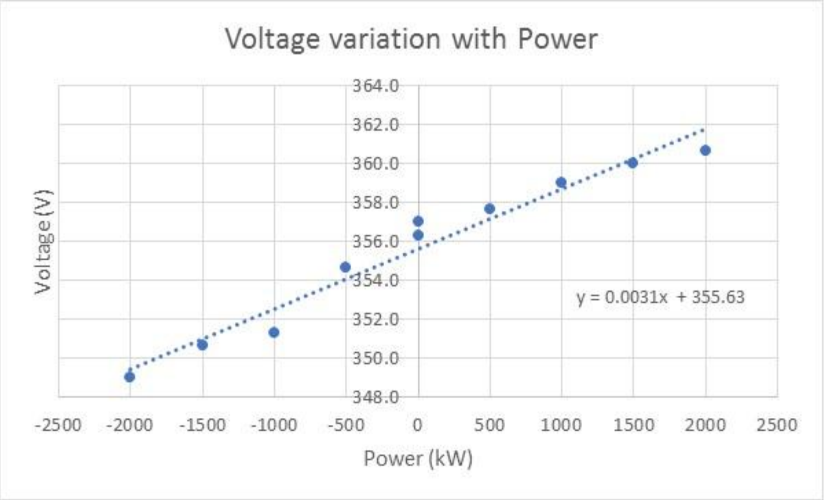


Fig. 5. Experimental variation of voltage at G59 relay with P set point, Q=0

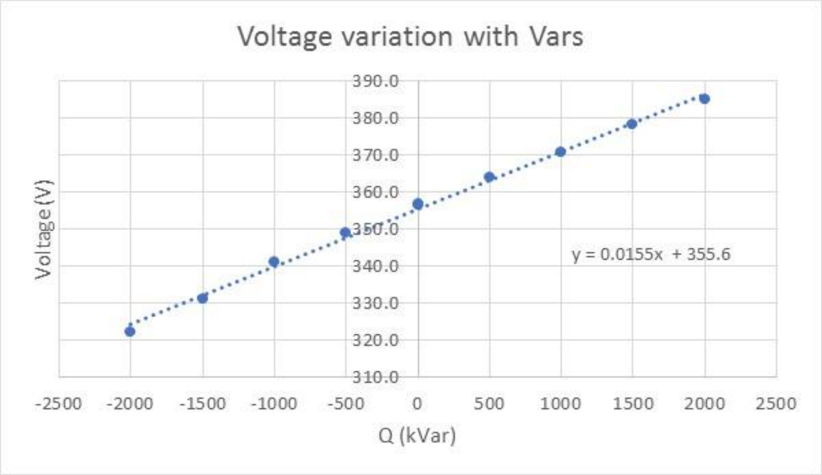


Fig. 6. Experimental variation of voltage at G59 relay with Q setpoint, P=0

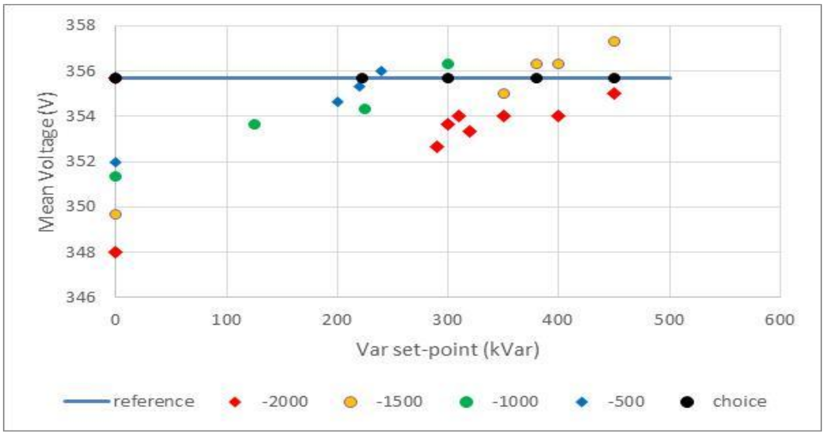


Fig. 7. Experimental variation of Q setpoint, for different values of P in kW when discharging

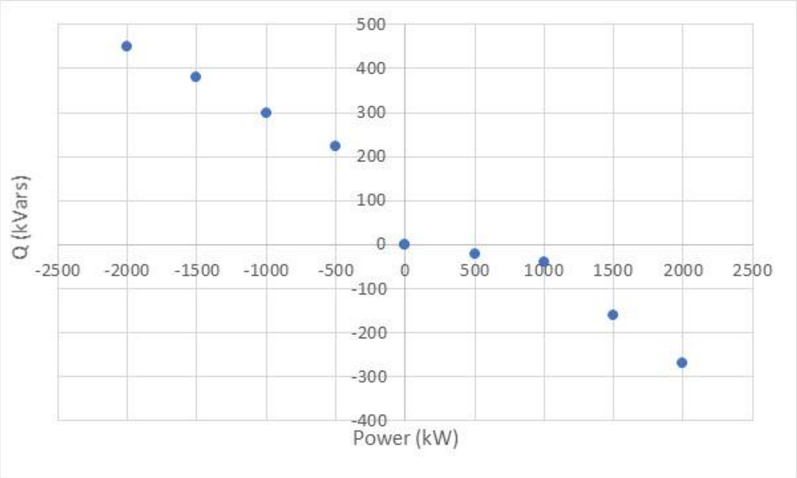


Fig. 8. P vs Q for a neutral voltage

Implementing this as a power factor function is more complex and yields the graph in Fig. 9. This is a very different shape from a constant power factor as suggested in reference [9] as an option.

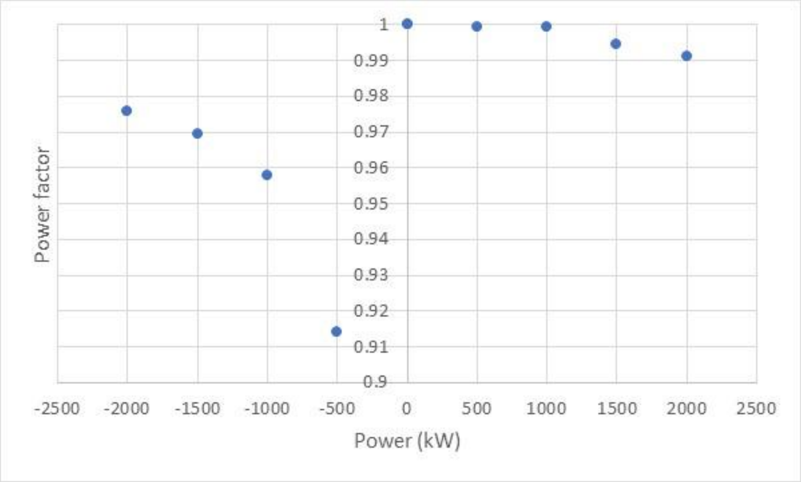


Fig. 9. Experimentally derived P vs power factor for a neutral voltage

Due to the variation of the Network voltage it is necessary to validate the impact of this “seagull” shape P/Q curve over a more extended test period. The Power was adjusted as a sawtooth waveform and the corresponding Vars for neutral voltage were coincidently set. A saw-toothed pattern was used so that subsequent patterns can be compared to help discount the impact of Network variation on the voltage measurement. The experimentally measured voltage is shown in Fig. 10. The Power and Vars are shown against the values on the left hand axis, while voltage is on the right hand axis. The horizontal black lines at constant voltage show what the max and min voltage would have been without the Var compensation based on the results in Fig. 4. The variable dotted red line shows the mean line voltage that is obtained experimentally. Although this is variable because of Network conditions, it is clearly more voltage neutral than without the compensation.

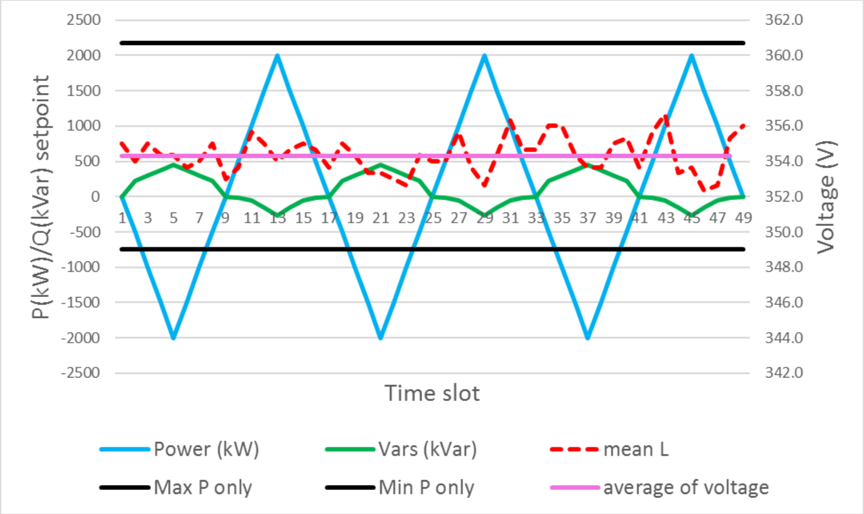


Fig. 10. Experimental variation of voltage with sawtooth variation of P and Q with time

4. Theoretical Modelling

The Willenhall system was modelled in Microcap as a variable P/Q generation source with equivalent impedance connected to a grid system as shown in Fig. 11. Table 1 represents the best guess estimate of the circuit impedance from the hardware referred to the LV. Z_1 is the approximate lumped impedance of the values from inverter, filter and cabling to the transformer and Z_2 is the network infeed, cabling and transformer impedance.

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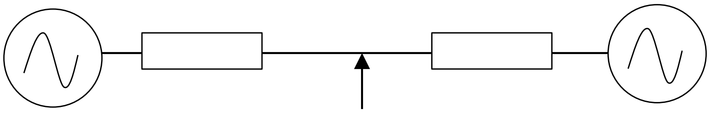

Fig. 11. Simplified computer model of Willenhall

Table 1. Model Parameters

Variable	Prefix	Value
LV Resistance	R1	1.44mΩ
ESS Filter Capacitance	C1	180µF
ESS Filter Inductance	L1	94.0 µH
ESS Filter Inductance	L2	47.0 µH
LV Inductance	L3	59.0 µH
Tx & Grid Resistance	R2	2.25mΩ
Strong Grid Tx & Grid Inductance	L4	1.60 µH

The P and Q setpoint values were coded into the model and the expected voltage was calculated as shown in Fig. 12 which can be compared directly to the experimental results obtained in Fig. 10. The obtained curve is not a perfect flat line around 355V, however, the values are well within the bands that would have been obtained (shown by the black lines) if no compensation had been added.

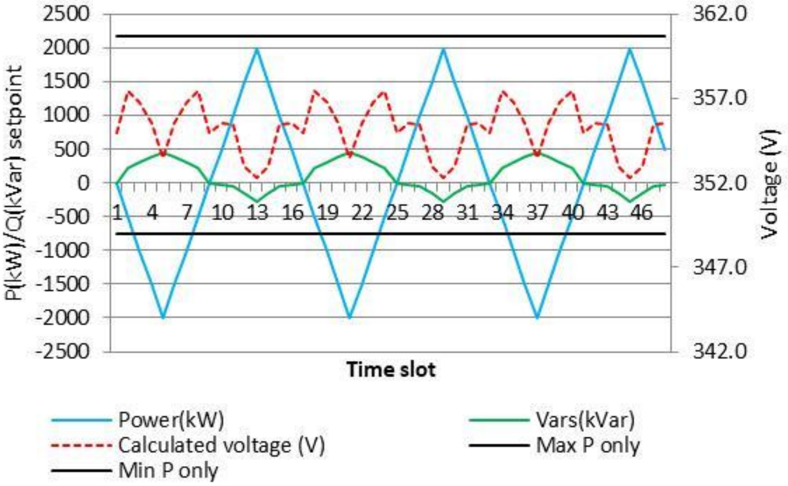

Fig. 12. Calculated variation of voltage for sawtooth variation of P and Q with time

This compares significantly more favorably than running the system at a fixed power factor of 0.95 as suggested in reference [9]. Running these values through the model results in very low voltage values at full power export as the Var values over compensate for the increase in voltage as shown in Fig. 13. This result echoes the results in Reference [9] where the voltage with fixed leading power factor correction was non-linearly much lower than that with unity power factor and equivalent lagging power factor during the course of a day on their PV panels.

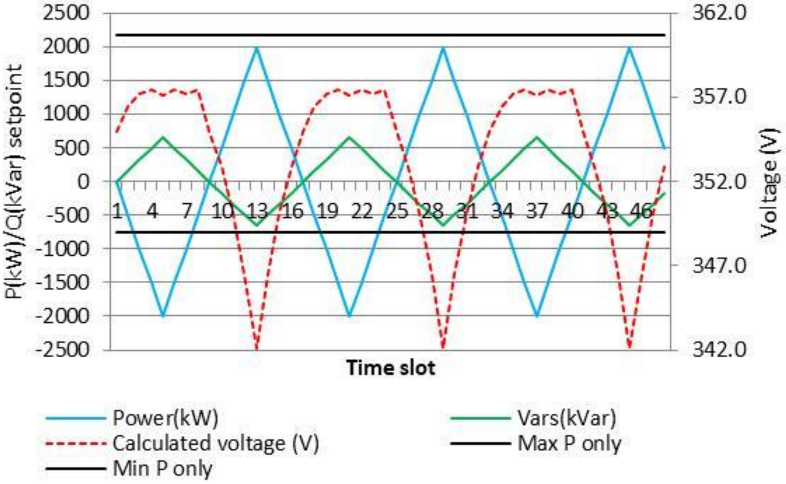

Fig. 13. Calculated variation of voltage for sawtooth variation of P and Q with time for a fixed power factor

5. Conclusion

There has been much research undertaken into voltage control of the distribution network. This has typically been split into two camps – utilizing an open loop - fixed power factor approach and using an active control method where the grid voltage is used as an input to determine the Var setpoint in an inverter connected system. The resultant curves in both cases are symmetrical with equal values of Capacities and Inductive Vars for a particular variation. The former approach is more straightforward to implement but modelling suggests that this does not give ideal results especially at maximum export condition.

The active approach is dependent on what the Network voltage is doing at the time and is a closed loop system where many inverters are adjusting their Vars with the aim of keeping an optimum voltage level. However there could be issues with systems fighting one another and long term stability. In addition, the droop curves are based on volts-vars and this may result in very low system power factors as the Vars try to compensate for Network voltage issues.

This paper has suggested an open loop control system as a more stable alternative, but has experimentally derived the required settings of the inverter, such that the grid connected inverter looks voltage neutral to the grid system. A key feature of this work is that the required Vars are not symmetrical for a variation in Power. This can be pre-coded as a P and Q lookup table in a “seagull” shape or as a power factor curve. Additional work is needed with different systems across different Networks to determine how appropriate this method is for all situations. However, it offers an improvement in terms of the fixed power factor method and is more predictable from a modelling and control perspective than the active method of control.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

S Morley undertook the literature review, S Royston designed and wired the experimental setup, S Royston, D Strickland and S Nejad undertook the experimental data collection, S Morley, S Royston and D Strickland undertook the modelling, analysis and documenting of the work, D A Stone, D Gladwin and M Foster reviewed the work and dealt with the operational and safety aspects of the site. All authors had approved the final version.

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