Utilizing Spare Inverter Capacity for Distribution Grid Voltage Support: An Adaptive Control Scheme

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Abstract—**Grid-tie inverters for connecting renewables to the grid are generally rated based on the peak power rating of the sources feeding them but, owing to the inherent variability and uncontrollability of most renewable energy sources, much of the inverter capacity is not used the majority of the time. This results in significant spare converter capacity that may be used for other purposes. This paper proposes an adaptive, plug-and-play means of utilizing this unused capacity for controlling reactive power, with the aim of providing grid voltage support on distribution networks, where reactive power control has traditionally not been economical. The method described uses an active impedance estimation algorithm to determine the gains required for reactive power controllers without requiring manual tuning of large numbers of converters. Both simulated and experimental results validating the techniques described are provided.**

Index Terms—grid voltage support, distribution voltage control, distributed generation, reactive power control, impedance estimation, spare inverter capacity

I. INTRODUCTION

Increasing numbers of power quality issues are expected to be observed as levels of renewable penetration increase worldwide. These issues include both long- and short-term voltage variations, a commonly reported concern of power engineers and caused by the inherent variability and limited controllability of renewable sources. Voltage quality issues include dips, swells and flicker, which are transient in nature, and may be caused, for instance, by sudden gusts of winds in wind power systems [1] or reflections on to photovoltaic (PV) generation [2]. Long-term variations in voltage may be caused by natural cycles in generation, such as PV generation, which will peak around midday and drop to zero during the night.

Controlling power system voltages is not a new problem and several solutions have been in use for a number of years. These include on-load tap changing (OLTC) transformers, static VAr controllers (SVC) and static compensators (STATCOM). While these devices have been used at high voltages, their use at lower distribution level voltages has been very limited for technical reasons, such as the large reactive power requirement needed to change voltage with an SVC or STATCOM [3]. Historically this has been only a minor issue, since generation was centralised and power flows tended to be unidirectional and regulating voltages at transmission level was sufficient to keep distribution level voltages within allowable limits. The deployment of renewable energy resources is causing a shift from traditional, centralised generation to widely distributed generation and, as a result, regulating transmission level voltages is unlikely to remain a sufficient means of keeping distribution voltages regulated.

Recent research has produced a number of proposals seeking to address the issue of voltage control on distribution systems. These include using dynamic voltage restorers (DVR) [4], which use a transformer with one winding connected in series with the line and the other winding connected to a power converter which can inject a controlled voltage when required. Unified Power Flow Controllers (UPFC), which have similarities to both DVRs and STATCOMs, have also been suggested for distribution network control [5], [6]. D-STATCOMs, which are STATCOMs optimised for use on distribution systems, have also been proposed [7]–[9]. Research has demonstrated that STATCOMs not only improve voltage quality but can also help improve network stability [10]. However, these solutions still require large current ratings and this can make stand-alone solutions prohibitively expensive. To overcome this it has been proposed that the spare capacity of the grid-tie inverters used to connect many renewable sources to the network may be used to provide voltage support when required [11], [12]. Although this does not overcome the large current requirements, it does allow the voltage support to be distributed over a large number of devices which are already present on the network. Such a solution does not require additional power electronic converters and overcomes the high-current rating requirement by spreading the current across a large number of converters. The spare capacity available from these converters is a side-effect of the inherent variability of renewable sources: the inverters themselves should be sized based on the peak generating capacity of the source to allow maximum energy export at times of high generation, but actual generation is likely to be lower much of the time.

In this paper the control of a D-STATCOM is considered. The STATCOM is not considered to be a standalone unit, but an additional function of an existing grid-tie inverter. Basic droop control is used to allow multiple converters to function in parallel without requiring communication between devices. Both single- and three-phase STATCOM implementations are considered. This paper specifically addresses the issue of automatically tuning the STATCOM AC voltage controller, which is achieved using grid impedance estimation, allowing key network parameters to be identified. Automatic tuning of the controller is required to overcome the need for time-consuming manual tuning of the converters by skilled installers, which is a likely barrier to the widespread adoption of this type of distributed voltage control. The applicability of grid impedance as a useful means of tuning reactive power controllers has been recognised in other work [13], [14].

This paper consists of three subsequent sections. Section II describes the proposed control scheme and controller tuning for both three-phase and single-phase implementations of the D-STATCOM. Section III provides both simulated and experimental results validating the proposals. Section IV summarises the findings of this work and concludes the paper.

II. THE PROPOSED GRID VOLTAGE CONTROL SCHEME

The method of reactive power control described in this paper was first proposed in [15] and later expanded in [16]. Whereas those earlier works were concerned purely with a dedicated converter configured solely for use as a STATCOM, this work is focused on the applicability of the same methods to a grid-tie inverter using spare capacity to provide the STATCOM functionality. In addition, this work also considers a single-phase implementation, whereas earlier work exclusively focused on three-phase systems.

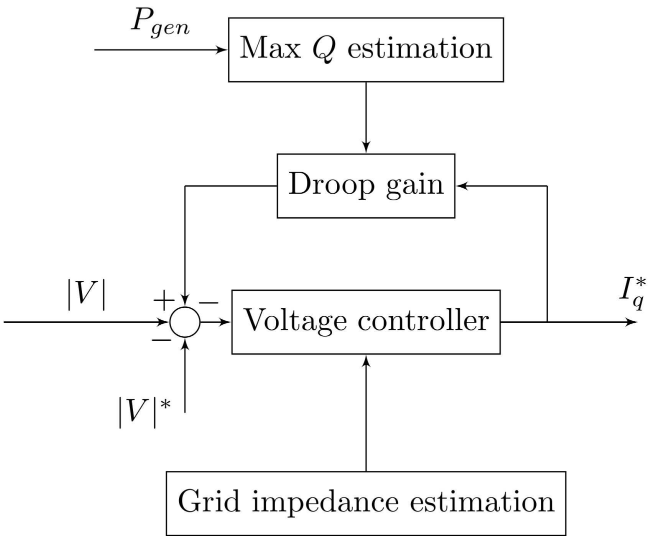

Fig. 1. A conceptual illustration of the grid voltage controller.

The control scheme requires three elements: the grid voltage controller which generates a reactive current demand in order to influence the network voltage; a grid impedance estimation method which is used to set the voltage controller gain; and a measurement of the spare inverter capacity which is used to adjust the droop gain of the voltage controller and impose limits on the maximum reactive power to be sourced or sunk by the converter. Fig. 1 shows the controller elements and how they interact with each other. The remainder of this section describes each element in detail.

A. Grid voltage controller

The grid voltage controller used in this work consists of an integrator with gain. The gain of the controller is variable to allow dynamic tuning during operation; the gain is proportional to the network reactance, X, and a fixed scaling factor is used to determine the desired speed of response. Reactance is chosen as the parameter for determining gain, since at a given grid voltage, V, the observed change in voltage, ΔV, caused by a change in reactive power flow, ΔQ, is approximately proportional to the network reactance. The relationship between changes in reactive power and changes in voltage is given in (1). Manipulating to determine the required reactive current to produce a desired change in voltage gives (2).

$$\Delta Q \approx -\Delta V \frac{V}{X} \tag{1}$$

$$\Delta I_q \approx -\frac{\Delta V}{X} \tag{2}$$

If ΔV is taken to be the difference between the desired grid voltage, V^*, and the actual instantaneous grid voltage, then the proposed controller can be viewed as determining the required reactive current to return the voltage to the desired value using the equation given in (3). The variable k represents the previously mentioned scaling factor, which is used to determine the speed at which the controller responds to changes in grid voltage.

$$I_q^*(t) = k \int \frac{(V(t) - V^*)}{X} \, \mathrm{d}t \tag{3}$$

Although variable the value of k is not entirely arbitrary and should be chosen with care. The value should not cause the bandwidth of the controller to exceed the grid frequency. Furthermore, the voltage controller should not have a much lower bandwidth than the inner current control loop which it feeds. Since the inner current control loop can be expected to have a bandwidth of 100 Hz or more, the bandwidth of the voltage controller can be set to any value upto 10 Hz without causing stability issues. In this work, the value of k is set to 20, which corresponds to a bandwidth of approximately 3.2 Hz for a correctly tuned controller.

In order to behave as expected, the controller must be tuned using an accurate estimate of the network reactance. A suitable means of estimating the reactance is described in Section II-B.

The described controller has two issues that should be addressed in order to be practical. Firstly, the controller will attempt to regulate the grid voltage to be exactly equal to the reference voltage. This degree of accuracy is not required for distribution networks, where some variation in actual grid voltage is allowed for. Even a small deviation from the reference voltage may result in a very large reactive current being supplied, which is not desirable. Secondly, the proposed controller is not well suited to systems where multiple parallel devices attempt to control the grid voltage, which is a key requirement of this work. Both issues may be addressed by using droop control, which may be implemented by including a small amount of negative feedback from the controller's output and using this to adjust the reference voltage. The droop gain must be calculated based on the ratings of the converter used for voltage control. Since this work is focussed on using spare inverter capacity to provide STATCOM functionality, the droop gain must be varied with the available inverter capacity. A method for real-time calculation of the actual droop gain is given in Section II-C.

B. Impedance estimation

The controller that has been described requires knowledge of the network reactance in order to function as expected. An estimate of the circuit reactance could be made and programmed into the converter during installation, although this is not desirable since it is time consuming, complicates the installation procedure and an erroneous or out-of-date entry cannot be corrected without repeating the process. Ideally the converter should include some functionality to estimate the network impedance during normal operation. This will simplify installation and commissioning procedures and invalid control parameters can be updated as required without the need for human intervention.

A number of different impedance estimation methods have been proposed. The one chosen to be used in this work is introduced in [17], [18]. The method was originally intended to be implemented on an active shunt filter used for harmonic filtering. To estimate the impedance, the PWM switching pattern of a power electronic converter is manipulated to inject a short current impulse of approximately one millisecond duration. This in turn creates a voltage disturbance on the network. Measurement of both the current impulse and the voltage disturbance can be used to determine the network impedance, Z. This is achieved by processing both measurements using a comb filter tuned to the fundamental network frequency, then taking the Fast Fourier Transform (FFT) of both voltage and current before dividing the frequency domain voltage, $\mathcal{F}(V)$, by the frequency domain current, $\mathcal{F}(I)$, as in (4).

$$Z = \frac{\mathcal{F}(V)}{\mathcal{F}(I)} \tag{4}$$

Once the impedance has been calculated, the reactance is found by considering only the imaginary part and ignoring the real (resistive) part. Only the reactance at the fundamental frequency is required and all other frequencies may be ignored. In theory, this may be extracted and used to set the controller gain. However, in practice, the estimated reactance at the fundamental frequency is likely to be affected by grid activity not caused by the injected transient and therefore an accurate impedance estimate will be difficult to achieve. For this reason, the fundamental impedance is extrapolated from impedance estimates at nearby inter-harmonic frequencies instead.

For this application, calculating the wideband impedance is unnecessary and computationally inefficient. It is therefore preferable to only calculate the impedance at the inter-harmonic frequencies used to interpolate the fundamental reactance. Calculation of the impedance at only the frequencies of interest may be achieved using a method known as Geortzel's Algortithm [19], as proposed in [16]. Rather than calculating the full FFT, the frequency domain voltage and current are calculated only at the frequencies of interest, as shown in (5) and (6), where V_ω and I_ω are respectively the single frequency voltage and current vectors, ω denotes the frequency in radians per second, for which the quantity is calculated and $v(t)$ and $i(t)$ are the time domain voltage and current respectively. The impedance at the chosen analysis frequency may then be calculated in the manner shown in (4).

$$V_\omega = \sum_{t=0}^{t=T} v(t) e^{-j\omega t} \tag{5}$$

$$I_\omega = \sum_{t=0}^{t=T} i(t) e^{-j\omega t} \tag{6}$$

This approach is computationally more efficient than requiring the calculation of the complete FFT for both current and voltage, which allows the method to be implemented in real-time without requiring significant and costly upgrades to the control hardware. In this work, a 50 Hz power system is considered and impedance values are extrapolated from estimates made at 80 Hz and 120 Hz. In order to achieve the desired frequency resolution the total data capture time, T, is 0.1 seconds. The proposed system may be applied to a 60 Hz system, although the impedance estimation frequencies should be chosen so that they do not clash with any harmonic frequencies.

C. Maximum reactive power output estimation

The proposed controller uses droop control, which results in an adjustment of the voltage reference based on the instantaneous reactive current demand. The adjustment is calculated based on the maximum available reactive current. The adjustment to the reference voltage may be calculated using (7). V_{nom} is the nominal grid voltage which would otherwise be used as the reference voltage and D is the droop constant. Calculation of the droop constant is achieved using (8) and requires knowledge of the maximum available current, $\hat{I}_q$, that can be used to generate reactive power. V_{min} is the minimum grid voltage which may still be regarded as within acceptable limits.

$$V^* = V_{nom} + D I_q \tag{7}$$

$$D = \frac{V_{nom} - V_{min}}{\hat{I}_q} \tag{8}$$

For a converter behaving solely as a STATCOM calculation of the droop constant is not an issue since the available reactive current is equal to the current rating of the converter and therefore the value needs only to be calculated once. However, where only the converter's spare capacity is available for STATCOM functionality, as is the case in this work, the droop settings must be constantly adjusted in order to track the available current. Calculation of the available current is achieved using (9), where P is the instantaneous real power being exported by the converter and S is the apparent power (VA) rating of the converter.

$$\hat{I}_q = \frac{\sqrt{S^2 - P^2}}{V} \tag{9}$$

The varying droop constant may now be calculated by substituting (9) into (8) to produce an expression which varies with the instantaneous export power of the inverter. In addition to being used to calculate the varying droop constant, the value of $\hat{I}_q$ also allows upper and lower limits of the grid voltage controller to be adjusted to reflect the available spare capacity from the inverter.

Combining the three elements described in this section produces the complete voltage control strategy used in this work. The controller outputs a reactive current demand which may then be fed into the controller for the grid-tie inverter, allowing full control of both the inverter's real power export and reactive power. The remainder of this paper focusses on validating the proposed control strategy using both experimental and simulated tests.

III. Simulated and Experimental Method Validation

A. Three-phase simulations

A three-phase system has been simulated. The total rating of the system is 315 kVA and the grid supply is represented as an ideal voltage source connected through a 5 mΩ resistance in series with an 80 μH inductance on each phase, representing the impedance of a transformer. The system is split into three sections, each separated by a 2 mΩ resistance in series with a 4 μH inductance for each phase representing a length of cable. Each section includes a grid-tie inverter rated at 33 kVA and a load of 100 kW with a lagging power factor of 0.9. The sections are identified as Zone 1, Zone 2 and Zone 3. Zone 1 is closest to the supply.

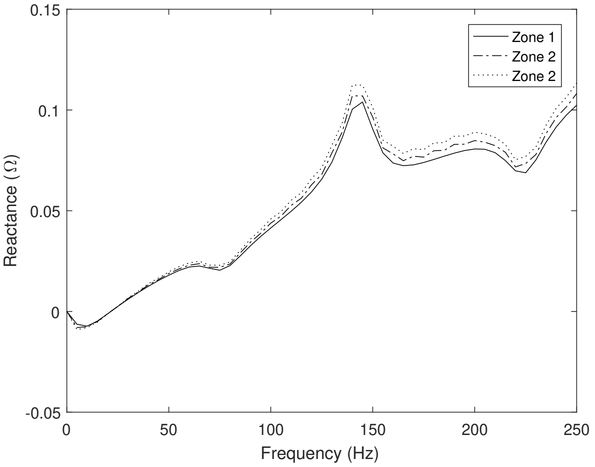

Fig. 2. Wideband estimate of the circuit reactance seen by each STATCOM on the three phase system.

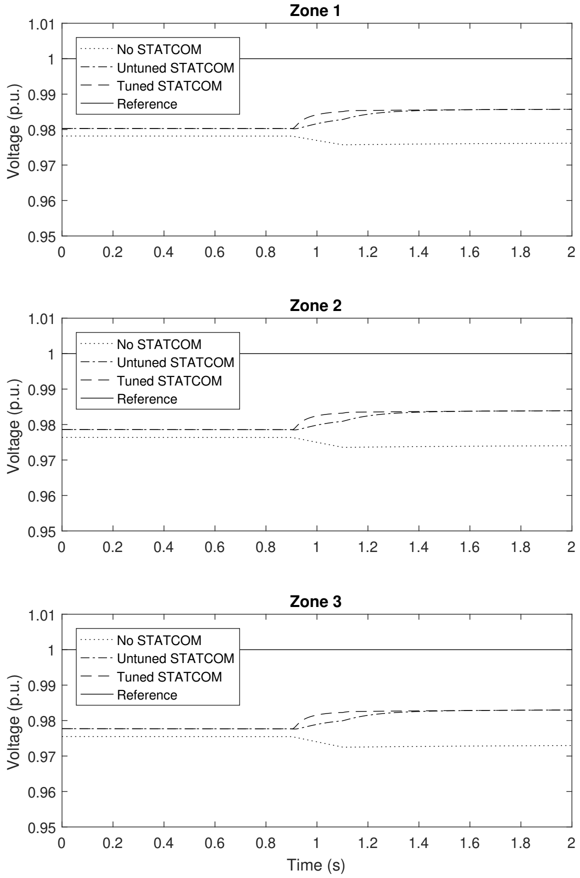

Fig. 3. Results for the three phase simulation with a generation output change.

The network impedance is estimated and used to tune the STATCOM controllers. The three converters each inject once onto each phase. Impedance estimation results for the three phases are averaged to give the reactance value used to tune the controllers. Although processing for control purposes is only performed at two frequencies, wideband results are presented here to illustrate what can be achieved using the described impedance estimation technique. Results are shown in Fig. 2. Although some frequencies, most notable around 50 Hz and

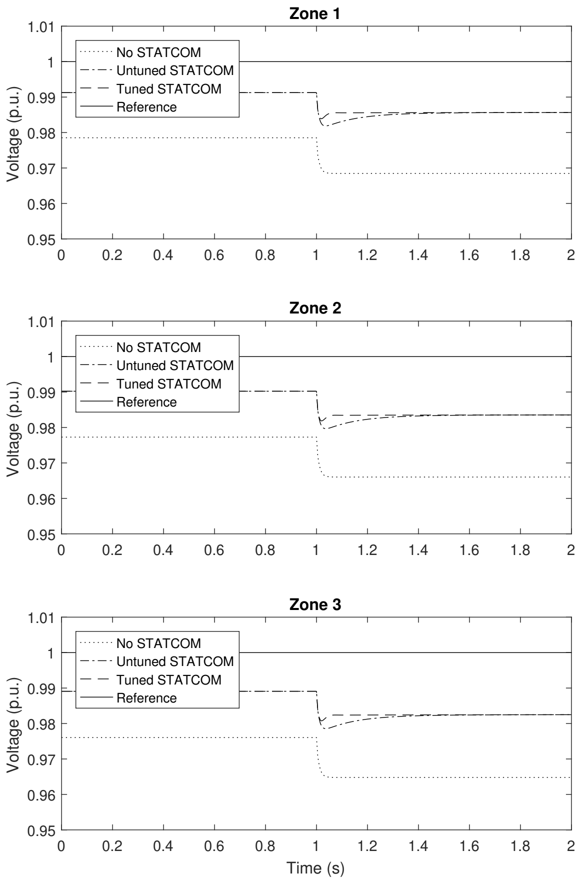

Fig. 4. Results for the three phase simulation with a load change.

150 Hz, are clearly effected by leakage from the supply frequency and harmonics, the overall quality of the results is sufficient for the fundamental reactance to be extrapolated from the 80 Hz and 120 Hz reactances.

Three simulations have been performed. In the first simulation the grid-tie inverters do not include STATCOM functionality. In the second, STATCOM functionality is included but the controller is not tuned to the network. The third simulation considers the system behaviour when STATCOM functionality is included and the controller is tuned to the network reactance. In order to demonstrate the dynamic benefits of the STATCOM functionality there is a rapid fall in generation midway through each simulation. The results from these simulations are shown in Fig. 3. It can be seen that the tuned controller reaches the new voltage more quickly than the untuned controller and that both tuned and untuned controllers raise the voltage to a level closer to the reference voltage than is observed in the no STATCOM scenario. The responses of the STATCOMs in each of the three zones are very similar. If the STATCOMs had been incorrectly tuned this would not be the case. In the untuned STATCOM simulation the similarity is caused by each STATCOM having the same gain and the impedance between STATCOMs being small. STATCOMs connected to the network through significantly different impedances would have widely differing responses to each other.

To further demonstrate the benefits of a correctly tuned controller, additional simulations have been performed featuring a load change of 33 kW midway through the simulation. Results of this simulation are shown in Fig. 4. From the results it can be seen that the settling time of the tuned controller is less than the untuned controller and stability is not compromised. Both tuned and untuned STATCOMs raise the voltage to a level closer to the reference than the no STATCOM scenario.

B. *Experimental results for a three-phase system*

In order to validate the simulation results, a three-phase STATCOM has been tested on an experimental power system. The STATCOM is capable of providing up to 40 A of leading or lagging reactive power. The experimental STATCOM does not include any generation and therefore no real power is exported from the unit. Furthermore, owing to the relatively small voltage changes caused by the STATCOM on the experimental system, droop control is not used. The supply inductance of the experimental network is 250 μH. A load change is used to cause a voltage drop. Experimental results for a tuned controller are compared to a simulation of the experimental power system to demonstrate consistency.

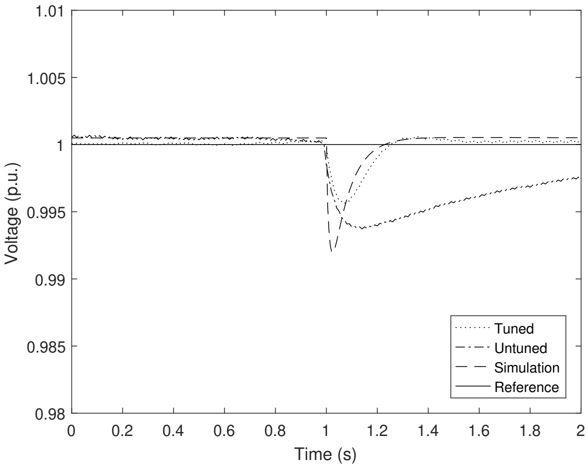

Fig. 5. Results for the single phase simulation with a load change.

Results are shown in Fig. 5. It can be seen that both tuned and untuned controllers are able to control the voltage to equal the reference voltage, but that the tuned controller has a faster response time without compromising network stability. There is close, although not perfect, agreement between the tuned controller and the simulated controller. Some differences are expected since the simulation will never fully represent the experimental system and the impedance estimation on a real system will be subjected to noise and errors not seen in simulation. The observed level of consistency between real and simulated controllers is sufficient to regard the control scheme as having been validated.

C. Single-phase simulations

Having simulated a three-phase system and used experimental results to demonstrate consistency between simulated and real performance, the proposed control principles have been applied to a single-phase system. Single-phase simulations have been performed on the same system used for the three-phase simulations, but with two phases removed and the loads connected phase-to-neutral rather than phase-to-phase. The ratings of the loads and grid-tie inverters are only one third of the ratings used for the three-phase system although the transformer and cable impedances remain the same. The simulations performed are the same as those performed for the three-phase system.

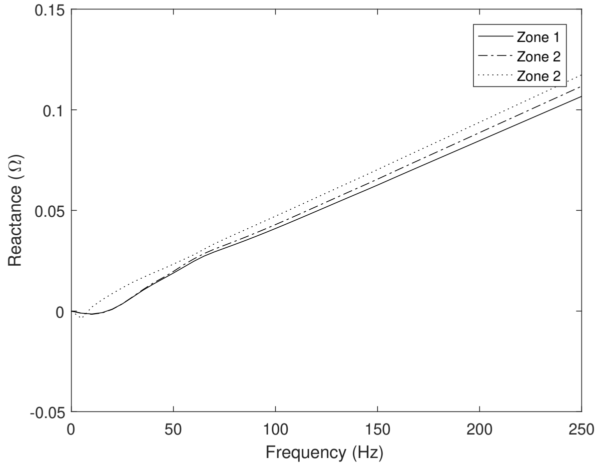

Fig. 6. Wideband estimate of the circuit reactance seen by each STATCOM on the single phase system.

Fig. 6 shows the wideband reactance estimation results for each of the three grid-tie inverters. As with the three-phase simulations, errors are evident at low frequencies and near 50 Hz. However, using Goertzel's Algorithm and the extrapolation method described in Section II the three reactances can be identified with sufficient accuracy for the controller to function correctly.

Fig. 7 shows the simulation results when a drop in exported real power is considered. As can be seen, the tuned STATCOM shows a slight improvement in settling time when compared to the untuned STATCOM. Both the tuned and untuned STATCOMs raise the voltage closer to the reference voltage compared to the no STATCOM scenario where the voltage is seen to fall when generation is reduced.

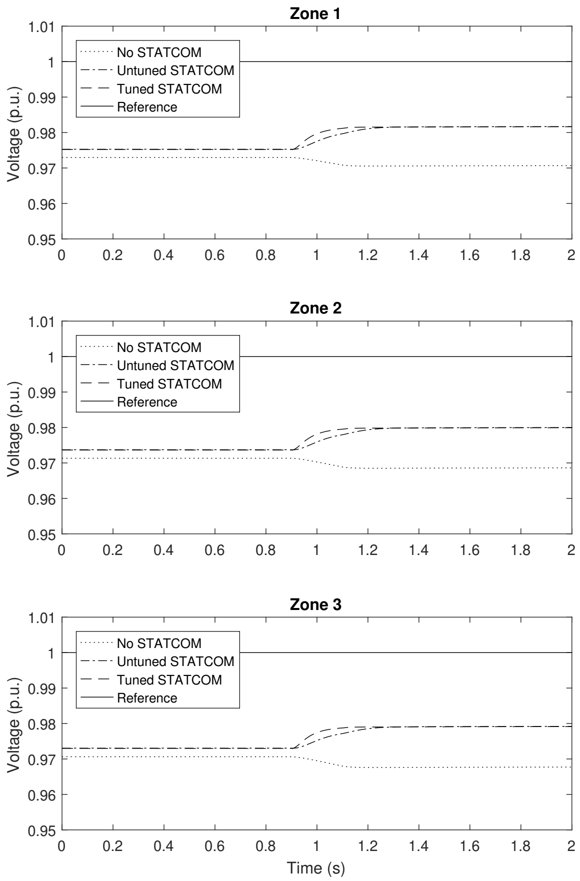

Fig. 7. Results for the single phase simulation with a generation output change.

Fig. 8 shows the simulation results when considering a step change in load. As with the results for a change in generation, the tuned STATCOM has a shorter settling time than the untuned STATCOM. The voltage falls as expected but is still closer to the reference voltage than the no STATCOM scenario.

General behaviour of the single-phase system is broadly similar to the three-phase system. However, simulations for both a reduction in generation and a step change in load show a slow voltage response even in the no STATCOM scenario. This is a consequence of the phase-locked loop (PLL) used to synchronise the inverter control to the grid, which is also used to determine the voltage magnitude. For the three-phase controller, the PLL may be designed with a relatively high bandwidth compared to the single-phase controller. The three-phase PLL has three reference voltages which can be used to calculate the voltage magnitude while the single phase PLL has only one and must wait for at least one half-cycle (10 ms) before updating the measured voltage magnitude.

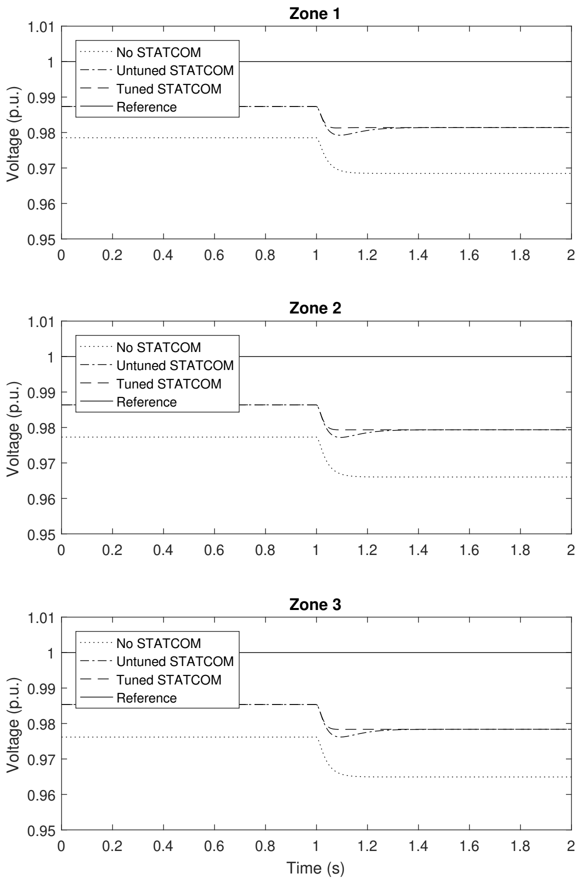

Fig. 8. Results for the single phase simulation with a load change.

IV. CONCLUSIONS

This paper has described a method of controlling distribution network voltages using the spare capacity from grid-tie inverters used for the integration of renewable generation to the grid rather than requiring additional standalone hardware. A controller tuning technique based on real-time grid impedance estimation is proposed as a means of allowing devices to behave in a "plug-and-play" manner following installation, reducing the time and cost associated with widespread deployment. Droop control is used to allow multiple units to operate efficiently in parallel without compromising network stability. Simulation has been used to demonstrate both single- and three-phase implementations of the proposed controller and further validation has been provided through laboratory testing using a three-phase power converter.

Comparisons have been made between situations where the grid-tie inverters include STATCOM functionality and situations where they do not. The STATCOM functionality helps to improve the voltage quality during times of rapidly varying generation. Only a 400 V network has been considered in this paper. At higher voltages, e.g. 11 kV, the STATCOM would be expected to show improved performance, since higher voltage networks tend to have higher supply inductances and higher $^{X}/_{R}$ ratios, making reactive power a more efficient means of controlling voltage. A truly distributed solution requires control at all voltage levels and therefore future work will focus on extending the research presented here to higher voltage distribution networks.

Further work is required to determine the appropriate criteria used to triggering retuning of the gird voltage controller. The impedance estimation method proposed causes a grid disturbance and should therefore be used sparingly. There is also the potential for multiple injections from different sources interfering with each other, resulting in impedance estimation errors and a method of preventing this is required. Both these problems should be explored as part of future research in this area.

REFERENCES

[1] A. A. Bahheri and H. Samet, "Extremely short time modeling of wind power variations", *International Journal of Renewable Energy Research*, vol. 8, no. 2, pp. 1046—1061, 2018

[2] R. Inzunza, Y. Tawada, M. Furukawa, N. Shibata, T. Sumiya, T. Tanaka and M. Kinoshita, "Behaviour of a photovoltaic inverter under sudden increase in irradiance due to reflection in clouds", 4^{th} *International Conference on Renewable Energy Research and Applications*, 22—25 Nov. 2015, Palermo, Italy

[3] T. L. Lee, S. H. Hu and Y. H. Chan, "D-STATCOM with positive sequence admittance and negative sequence conductance to mitigate voltage fluctuations in high-level penetration of distributed-generation systems", *IEEE Trans. on Industrial Electronics*, vol. 60, no. 4, pp.1417—1428, April 2013

[4] K. Sudheer and S. Ramasamy, "Mitigating voltage imperfections with photovoltaic fed ANFIS based ZSI-DVR in three phase system", *International Journal of Renewable Energy Research*, vol. 7, no. 4, pp. 2103—2110, 2017

[5] T. Maekawa, T. Takeshita and Y. Kunii, "Node voltage control and line loss suppression using unified power flow controller on distribution system", 4^{th} *International Conference on Renewable Energy Research and Applications*, 22—25 Nov. 2015, Palermo, Italy

[6] M. Kano, T. Maekawa, T. Takeshita and Y. Kunii, "Comparison of converter arrangement of series and shunt converters in UPFC for distribution system control", 5^{th} *International Conference on Renewable Energy Research and Applications*, 20—23 Nov. 2016, Birmingham, UK

[7] M. Thirupathaiah, P. Venkata Prasad and V. Ganesh, "Enhancement of power quality in wind power distribution system by using hybrid PSO-Firefly based DSTATCOM", *International Journal of Renewable Energy Research*, vol. 8, no. 2, pp. 1138—1154, 2018

[8] G. Muni Reddy and T. Gowri Manohar, "Fuzzy logic controller based STATCOM for grid connected wind turbine system", *International Journal of Renewable Energy Research*, vol. 8, no. 2, pp. 702—713, 2018

[9] Y. Sugahara and T. Takeshita, "Reactive current control of a multi-DC-voltage cascade STATCOM", 4^{th} *International Conference on Renewable Energy Research and Applications*, 22—25 Nov. 2015, Palermo, Italy

[10] F. Selwa, L. Djamel, L. Imen and S. Hassiba, "Impact of PSS and STATCOM on transient stability of multi-machine power system connected to PV generation", 4^{th} *International Conference on Renewable Energy Research and Applications*, 22—25 Nov. 2015, Palermo, Italy

[11] M. Thomson, I. Richardson, J. P. Barton and D. G. Infield, "Distributed automatic voltage control (DAVC)", *CIRED* 20^{th} *International Conference on Electricity Distribution*, 8—11 June 2009, Prague, Czech Republic

[12] V. R.Gasiyarov, A. S. Maklakov, R. A. Lisovski, "Grid power control of medium voltage AC drives based on back-to-back converters", *2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, 29 Jan.—1 Feb. 2018, Moscow, Russia

[13] H. H. Tumbeleka, E. Muljadi and W. Gao, “The impact of transformer winding connections of a grid-connected PV on voltage quality improvement”, *International Journal of Renewable Energy Research*, Vol. 8, No. 1, pp. 8—14, 2018

[14] J. De Kooning, J. Van de Vyver, J. D. M. De Kooning, T. L. Vandoorn and L. Vandevelde, “Grid voltage control with wind turbine inverters by using grid impedance estimation”, 3^{rd} *IET International Conference on Renewable Power Generation (RPG)*, 24—25 Sept. 2014, Naples, Italy

[15] C. Rose, M. Sumner, D. W. P. Thomas and E. Christopher, “Impedance sensitive STATCOM control for systems supported by renewable generation”, 3^{rd} *IET International Conference on Renewable Power Generation (RPG)*, 24—25 Sept. 2014, Naples, Italy

[16] C. Rose, “An adaptive D-STATCOM control scheme utilising impedance estimation”, PhD thesis, University of Nottingham, 2016

[17] M. Sumner, B. Palethorpe and D. W. P. Thomas, “Impedance measurement for improved power quality – part 1: the measurement technique”, *IEEE Trans. on Power Deliver*, vol. 19, no. 3, pp. 1442—1448, 2004

[18] M. Sumner, B. Palethorpe and D. W. P. Thomas, “Impedance measurement for improved power quality – part 2: a new technique for stand-alone active shunt filter control”, *IEEE Trans. on Power Deliver*, vol. 19, no. 3, pp. 1457—1463, 2004

[19] G. Goertzel, “An algorithm for the evaluation of finite trigonometric series”, *The American Mathematical Monthly*, vol. 65, no. 1, pp. 34—35, 1958