Impedance sensitive STATCOM control for systems supported by renewable generation

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Abstract

Reactive power control is known to be an effective means of controlling voltage; however, for optimal performance, the system reactance must be known. Power systems with high renewable energy penetration have been known to have voltage stability issues. To further complicate this issue, distributed renewable sources are likely to have an effect on the local system impedance. As a result, connection and disconnection of such sources is likely to result in significant changes in system impedance. In this paper, impedance estimation is used to dynamically tune the controllers of a STATCOM so that consistent dynamic performance may be obtained. The method has been verified through simulation and through laboratory-based experimentation.

1 Introduction

Distributed generation (DG) can reduce the transportation cost of electricity and has the potential to improve power system efficiency and reduce carbon emissions [1]. However, the use of DG, which can include renewable technologies introduces so-called penetration issues: problems which arise due to the presence of DG on the electrical network. For example, many sources of renewable energy supply the maximum available power to the grid. The available power may vary considerably and erratically, particularly for wind and solar sources, which can lead to voltage stability issues [2, 3, 4].

There is a strong relationship between AC power system voltage and reactive power flow [5]; it is therefore possible to control the system voltage by either injecting or absorbing reactive power as needed. The relationship between reactive power and voltage is largely dependant on the system reactance. Therefore, for optimal voltage control, the system reactance must be known. Since the system impedance of areas with high renewable penetration may well vary as local supplies switch on and off, a means of determining the reactance is required in order to maintain optimal performance.

STATCOMs can offer a fast, flexible and efficient means of both absorbing and injecting reactive power, thereby regulating grid voltage. However, there has been only limited study of STATCOM control parameters [6]. In most cases the controller parameters are configured through trial-and-error. As a result, the STATCOM performance will vary considerably with variations in system configuration.

In this paper, a means of estimating grid impedance and retuning the STATCOM controllers to the newly identified system reactance is proposed. Simulation work has been performed to study the proposed method and this has been followed up with laboratory-based experimental work.

2 Proposed control strategy

2.1 The STATCOM AC voltage controller

The basic control structure for a STATCOM is shown in Figure 1. The DQ coordinate system is used because it allows the DC link controller and AC voltage controller to be treated separately. In such a system, the d-axis current, I_d, is the component of the converter current which is in-phase with the voltage at the converter terminals; while the q-axis current, I_q, is the component of the converter current which is $90°$ out of phase with the system voltage. Therefore, only the d-axis current contributes to the real-power used by the converter and only q-axis current contributes to the reactive power supplied or absorbed by the converter. $\mathrm{I_d}$ and $\mathrm{I_q}$ may be controlled independently.

Although the design of the DC link voltage control and AC current control is well documented and understood [7], the design of the AC voltage regulators has received only limited attention in existing literature. PI controllers are often used, but the gains are generally fixed and set empirically, leading to an inflexible and potentially non-optimal design [6].

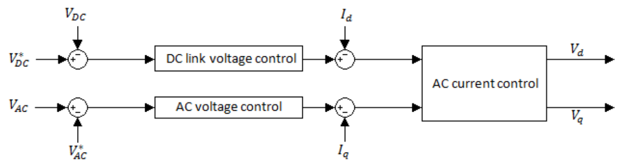

Fig. 1: General STATCOM control structure.

To understand the design requirements of the AC voltage controller, it is first necessary to consider the relationship between AC voltage and reactive power.

A predominantly reactive power line having per-phase reactance X, with voltage magnitude V_s, at the sending end and voltage magnitude V_r, at the receiving end and a phase displacement, θ, between them, the reactive power in the line is given by:

$$Q = \frac{V_s V_r \cos\theta - V_r^2}{X}. \tag{1}$$

Differentiating with respect to V_r, it can be seen that a change in reactive power, ΔQ caused by a change in receiving end voltage, ΔV_r, is therefore:

$$\Delta Q = \frac{V_s \cos\theta - 2V_r}{X} \Delta V_r. \tag{2}$$

Given that θ is normally small and assuming that the receiving end voltage is approximately equal to the sending end voltage, Equation (2) may be simplified to:

$$\Delta Q \approx \frac{-V_r}{X} \Delta V_r. \tag{3}$$

The change in magnitude of reactive current, I_q, flowing from the sending to the receiving end of the line for a given change in voltage is then:

$$\Delta I_{qsr} = \frac{\Delta Q}{V_r} \approx -\frac{1}{X} \Delta V_r. \tag{4}$$

From Equation (4), it is observed that an integral controller may be designed. This will give a first order response with time-constant τ. If ΔV_r is taken to be the voltage error, then the magnitude of the reactive current demand, I_q^*, at time T is given by:

$$I_q^* = -\frac{1}{\tau X} \int_0^T \Delta V_r \, \mathrm{d}t = -\frac{1}{\tau X} \int_0^T (V_r^* - V_r) \, \mathrm{d}t. \tag{5}$$

The proposed STATCOM voltage controller is shown in Figure 2. The fixed gain is set to give the desired time constant, τ. The variable gain, shown as a multiplier, is adjusted in order to tune the controller to the system reactance, X.

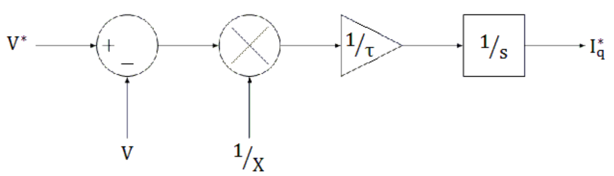

Fig. 2: The proposed STATCOM voltage controller.

2.2 Controller retuning

It can be seen above that the system reactance has a significant effect on the controller dynamics. The controller will give the desired response only if the supply reactance is known and has been used to tune the controller gain. Since it is possible for the system reactance to vary, particularly for systems with high DG penetration or where the load impedance is not insignificant with respect to supply impedance, a method of identifying the system reactance and retuning the STATCOM controller is needed.

Active Impedance Estimation (AIE), the method proposed in this paper for retuning the STATCOM AC voltage controller was first presented for use in active filter control [8]. AIE is a method for estimating the system impedance by using a power electronic converter to introduce a small, short-term, current disturbance to the system. For the study presented in this paper, the method is implemented using power electronics present in the STATCOM. The current injection is 1 ms in duration and the amplitude is limited by the STATCOM filter.

The injected current causes a voltage disturbance. Both disturbances are captured and processed to obtain the system impedance. In total, 0.2 s of both voltage and current data is captured, with the injection occurring during the second half of the captured data. To remove the fundamental and harmonic content from the captured data such that only the injection remains, the first half (“pre-injection data”) of the captured data is subtracted from the second half (“post-injection data”):

$$V_{inj} = V_{post-injection} - V_{pre-injection}. \tag{6}$$

$$I_{inj} = I_{post-injection} - I_{pre-injection}. \tag{7}$$

Once the fundamental and harmonic components are removed from the captured data, the impedance is calculated using the DFTs of the voltage and current:

$$Z = \frac{\mathcal{F}(V_{inj})}{\mathcal{F}(I_{inj})}. \tag{8}$$

The imaginary part of the estimated impedance at the system fundamental frequency can then be used to retune the STATCOM controller. For the results presented in this paper, the impedance of each phase was estimated individually, and the average of the three used to retune the controller. Curve fitting of the results may also be used to improve the impedance estimate.

3 Modelling and experimental study and results

3.1 Simulation based study

Various simulations were performed using Simulink and the PLECS blockset [9] to confirm the theoretical study. Initial simulations were used to confirm that the proposed control scheme and the controller tuning method were effective. Later simulations studied the STATCOM performance over a wider range of operating conditions.

To study the effect on STATCOM performance of a local renewable supply being switched nearby and to verify the efficacy of the method, simulations were run using the system illustrated in Figure 3.

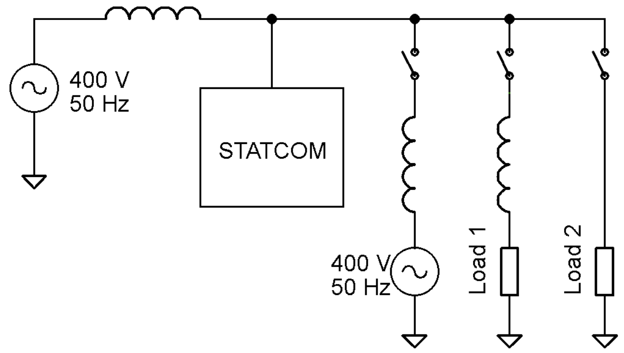

Fig. 3: Simplified schematic of the simulation circuit used to investigate the effect of local generation on STATCOM performance.

The main supply has a reactance of 500 μH per phase and the local supply has a reactance of 100 μH per phase. The simulations were used to show that the controller could be retuned following a significant change in system configuration, in this case, an additional supply was switched on, changing the system impedance and raising the voltage at the point where the STATCOM is connected. Load 1 consists of a 2.5 mH inductor in series with a 10 Ω resistor on each phase. Load 2 consists of a 5 Ω resistor on each phase. The fixed gain of the STATCOM voltage controller was chosen to give a time constant of 0.1 s when the controller is tuned.

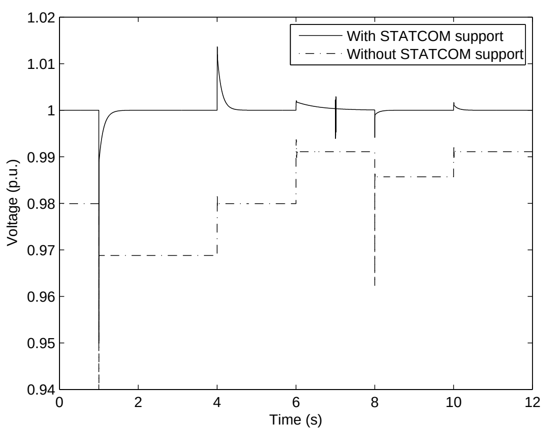

Fig. 4: Results for the system shown in Figure 3.1, both with and without STATCOM support.

Figure 4 shows the system response when an additional supply is connected for both a system without STATCOM support and one with STATCOM support. At t=1 s Load 1 is switched on. Load 2 is on for the duration of the test. Load 1 is switched off again at t=4 s. In both cases, the voltage returns to 1 p.u. with a time constant of 0.1 s. At t=6 s the local generation is switched on, causing a rise in system voltage. The time taken for the voltage to return to the 1 p.u. set-point has now increased considerably. The controller is retuned to the new supply impedance. Following retuning, the controller has the desired response, as seen when Load 1 is switched on again at t=8 s and off again at t=10 s. The injections used for impedance estimation can be seen at t$\approx$ 7 s.

To more realistically model the impact of renewable energy sources on the STATCOM performance, the local supply in Figure 3 was replaced with a simplified model of a grid-tie inverter controlled using some form of maximum power point tracking (MPPT), as shown in Figure 5. The model is intended to be representative of a voltage source converter with an LCL filter on the output. It has been assumed that the output impedance seen by AIE will be dominated by the grid-side inductor and filter capacitor, with the converter side inductor and converter itself approximated by a current source.

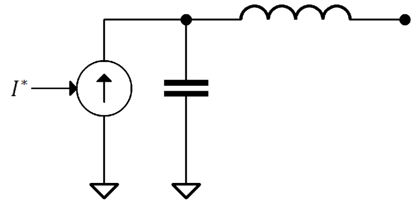

Fig. 5: A single phase of the grid-tie inverter model used during simulation.

The current source is controlled so that the current flowing through the inductor to the grid is in phase with the grid voltage. The magnitude of the current is fixed, resulting in a roughly constant power being supplied by the inverter when it is connected to the grid, similar to the behaviour expected from grid-tie inverters employing MPPT.

Results from simulations for including the inverter model are shown in Figure 6. The tests are the same as those described above, except for the change in the local supply model. At time t=6 s the inverter is switched on and begins supplying 75 A to the system. As a result, the system voltage initially rises and then begins to oscillate. These results illustrate that the STATCOM is able to damp those oscillations. Comparing the results for a fixed controller with those for the tuning controller show that the quality of the damping is dependent on the controller gain.

3.2 Experimental verification

Practical verification of the method was performed using the experimental set up shown in Figure 7. Three loads are switched to vary the current drawn from the supply, and therefore the voltage drop across the supply inductance.

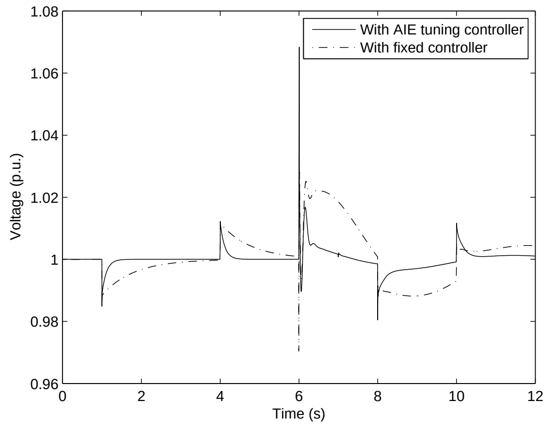

Fig. 6: Results for the simulation system when the grid-tie inverter model described is used in place of the local voltage source.

The supply inductance is intended to represent a long length of cable or the leakage inductance of a transformer and can be changed between 500 μH and 1 mH to show the effect of changing supply reactance. A large supply impedance was necessary to give a significant voltage drop because of the relatively low current rating of the system (32 A maximum).

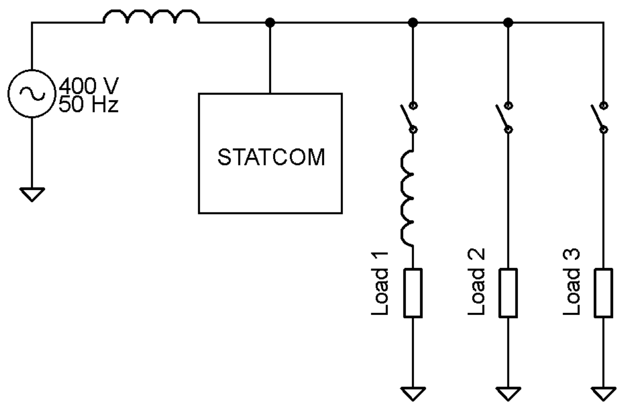

Fig. 7: A simplified diagram of the experimental set up used to verify the STATCOM control scheme.

The STATCOM was implemented using a 11 kVA Triphase power converter [10]. The configuration of the three loads is given in Table 1.

Load No.	R (Ω/ph)	L (mH/ph)	P (kW)	Q (kVAr)
1	12.0	10.0	13.5	3.5
2	57.6	0	3.0	0
3	57.6	0	3.0	0

Table 1: Load configuration for the experimental set up.

Tests were run for supply inductances of 500 μH and 1 mH with each of the loads being switched so that behaviour could be observed at several power levers. Both fixed controllers and tuning controllers were used in each test so that a comparison could be made between the two. In addition, control tests were run in order to compare the case of a STATCOM supported system to an unsupported system.

The fixed gain of the voltage controller was set to 1 to give a time constant of 1 s. No modifications were made to the current controller of the Triphase converter. Current injection for the impedance estimation was accomplished by slightly modifying the voltage demand input to the PWM generation subsystem.

3.3 Experimental results

Figure 8 shows the response of the STATCOM when the 14 kVA load (load 1) is switched on at the beginning of the test (at $t \approx 2\ s$ in the figure), and later off again (at $t \approx 45\ s$), for both the fixed gain controller and the tuning controller when the supply inductance is 1 mH. AIE identified the supply reactance as $0.34\ \Omega$ at 50 Hz (equivalent to a 1.08 mH inductance). Therefore, the variable gain of the controller was set to 2.9.

Both the fixed and the tuned controller are capable of regulating the supply voltage, however, the time constant of the tuned controller is 1 s, as expected. In a control test without STATCOM support, the system voltage drops to 0.982 p.u.

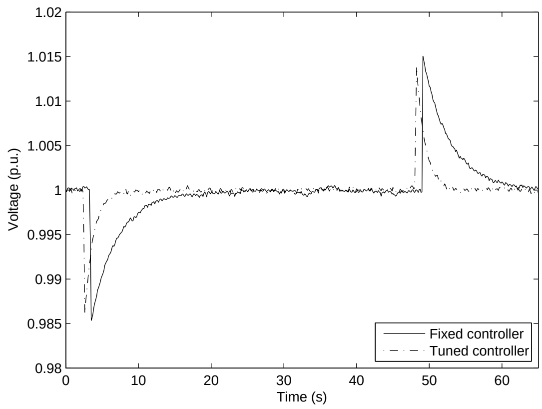

Fig. 8: Results comparing performace of a fixed controller to a tuning controller when a 14 kVA load is switched (1 mH supply impedance).

Figure 9 shows the peak reactive current supplied in order to achieve the voltage responses shown in Figure 8. The reactive power required to return the voltage to 1 p.u. is consistent with theory described earlier in this paper.

Figure 10 shows the same test as Figure 8 repeated for a system having a 500 μH supply inductance. In this case, AIE identified a 50 Hz reactance of $0.16\ \Omega$ (equivalent to an inductance of 510 μH). The variable gain was therefore set to 6.3. The control test was also repeated, resulting in a voltage of 0.988 p.u. without STATCOM support.

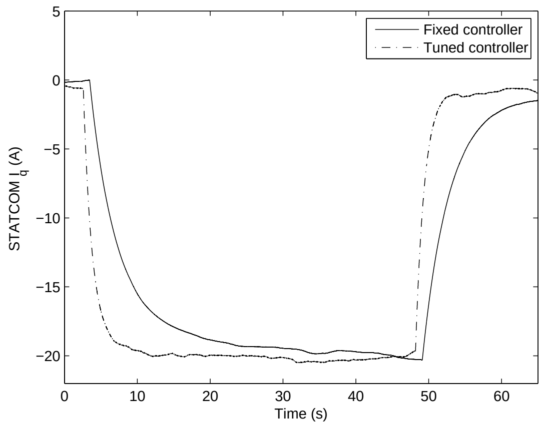

Fig. 9: Comparison of reactive current responses for a fixed controller and one which has been tuned using AIE.

Comparing Figures 8 and 10, it can be seen that the response of the fixed controller changes dramatically with a change in supply impedance, whereas the tuning controller has a consistent response, regardless of supply impedance, once tuned.

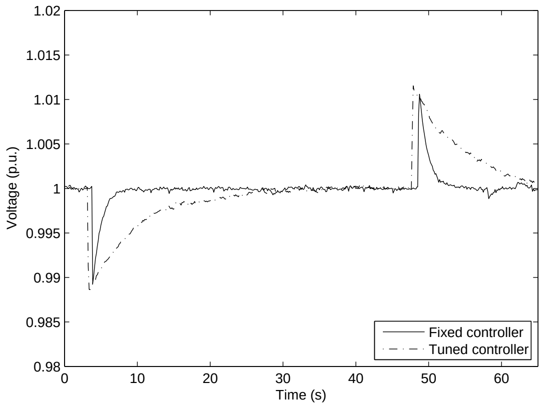

Fig. 10: As Figure 3.3, but with a 500 μH supply impedance.

Figure 11 shows a comparison of the tuned controller responses for a supply inductance of 1 mH with the response for a supply inductance of 500 μH, for the same switching test as is shown in Figures 8 and 10. In both cases, the controller time constant is 1 s, demonstrating that the control retuning has given the expected results.

4 Conclusions

This paper has considered the problem of voltage instability on power systems having high renewable generation. The use of small STATCOMs as a source and sink of reactive power has been suggested as a means of mitigating fluctuations in voltage. It has been noted that the system impedance, as seen from the point of connection of the STATCOM, has a significant impact on the dynamic performance of reactive power control. A method of retuning the AC voltage controller using impedance estimation has therefore been proposed. Simulation has been used to demonstrate the potential of the proposed method and this has been followed with a practical demonstration using a power converter and a laboratory-based demonstration system.

Future work is planned to further expand the demonstration system and to study the performance of the proposed method across a wider range of test conditions.

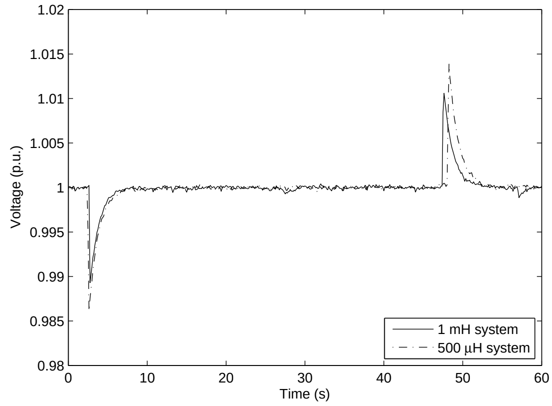

Fig. 11: Comparison of the performance of the tuned controller for a 500 μH supply and a 1 mH supply.

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