EFFECTIVENESS OF D-SVC ON RURAL NETWORKS

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ABSTRACT

This paper presents Hitachi's new D-SVC[1] (Static VAr Compensator for Distribution Networks), which has been designed to combat voltage fluctuation problems caused by DRG (Distributed Renewable Generation) on distribution networks. Voltage fluctuations occur within different time frames, hence the D-SVC has been designed to operate in several different modes of voltage control corresponding to each type of fluctuation. In phase one of a demonstration project sponsored by the UK government's LCNF (Low Carbon Network Fund), the D-SVC was installed adjacent to a windfarm in a rural 11kV distribution system to investigate the effectiveness of the D-SVC on voltage fluctuations caused by the windfarm. This paper describes the results obtained during this phase of the demonstration project.

BACKGROUND

In response to the threat posed by climate change caused by CO_2 emissions, European governments have set emission targets and incentivised the installation of DRG.

Although DRG addresses the issue of CO_2 emissions, its real power output is stochastic which in turn produces voltage fluctuations on the distribution system. Furthermore, this effect is amplified on weak distribution feeders such as those in rural areas.

European DNOs have a statutory obligation to maintain voltage within specific limits, and whilst there are a number of traditional solutions available, such as reinforcement, capacitor banks and auto-transformers, these can be costly and time consuming, especially when dealing with long rural feeders. New innovative solutions, such as the D-SVC, will allow more DRG to be connected and at the same time, enable control of the line voltage. The D-SVC reacts within milli-seconds to voltage changes on the network and thus is able to reduce voltage fluctuations.

D-SVC SYSTEM

Hitachi's new D-SVC is based on VSC (Voltage Source Converter) topology which utilises IGBTs (Insulated Gate Bipolar Transistors) as the main switching devices. The D-SVC can control reactive power by injecting 90° leading/lagging current as it converts DC current from its DC capacitors to AC current [1]. The D-SVC can achieve fast response rates to voltage change due to the high speed IGBTs.

The D-SVC used in this project was designed for voltage fluctuation suppression on distribution networks and has a capacity of 400 kVA (refer to Table 1). As shown in Figure 1, the D-SVC is of a single free-standing cabinet structure with a small footprint, thus minimising installation space.

Figure 1: Overview of D-SVC

The D-SVC has two key control modes. The first is autonomous operation with a choice of three different voltage control modes, designed to counter different voltage fluctuation time frames.

The second is remote operation using the built-in communication facility, which allows voltage control over multiple D-SVCs. In this scenario, a central server, D-VQC (Voltage and reactive power (Q) Control system for Distribution grid), calculates and sends the optimal reference voltage for each D-SVC through the communication facility. Each D-SVC will then coordinate its individual reactive power output. By adjusting the voltage of various points of a feeder using multiple D-SVCs, the voltage headroom on a given feeder can be increased and the power loss can be decreased [3].

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[1] Aka D-STATCOM

Table 1: D-SVC Specification

Item	Specification
Rated Capacity	400kVA (Capacitive and Inductive)
Rated Voltage	415kV
Rated Current	557A
Response time	Less than 20msec
Frequency	50Hz

D-SVC Structure

Figure 2 shows a simplified block diagram of a D-SVC. The D-SVC is connected to the feeder via an 11kV/415V transformer, with the D-SVC taking voltage and current measurements. From these measurements the D-SVC autonomous control system calculates the reactive current which in turn provides the input signal for IGBT switching and hence VAr injection.

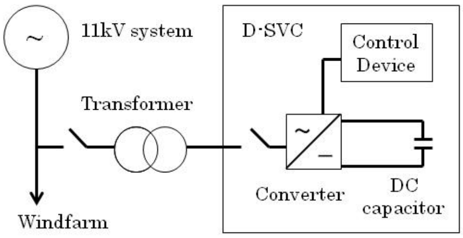


Figure 2: Structure of D-SVC

Voltage Controller

The function of the three modes (refer to Table 2) is explained below:

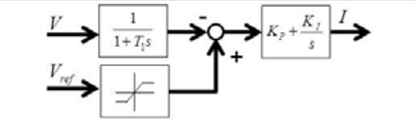
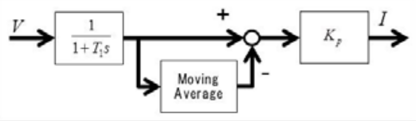
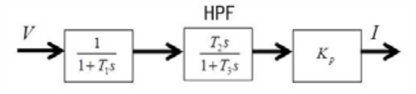
(1) AVR (Automatic Voltage Regulation) controller: The voltage at the point of D-SVC connection is maintained by controlling the supply of leading/lagging reactive power to adjust to the reference voltage. This mode is appropriate for maintaining the voltage close to a reference voltage.

(2) ARV (Average Reference Voltage) controller: The voltage at the point of D-SVC connection is maintained by controlling the supply of leading/lagging reactive power to adjust to the average of the voltage over several minutes. This mode is effective for longer term voltage variations.

(3) SFV (Short-term Fluctuation of Voltage) controller: The D-SVC operates at fast response rates for short-term fluctuations of voltage. Output of the D-SVC is reduced to allow it to prepare for the next voltage drop. This mode is effective for reducing voltage flicker [2].

Table 2 shows basic block diagrams of the three modes of voltage control. The D-SVC can also be used in conjunction with an SVR (Step Voltage Regulator) to control larger voltage fluctuations. However, if the D-SVC is simply operated at the same time as a SVR, the capacity of D-SVC will be saturated before the SVR reacts, thus the D-SVC no longer has any capacity to supply additional reactive power. To solve this, the D-SVC can be programmed to operate using a combination of ARV controller and SFV controller at the same time. When a voltage drop occurs, the SFV controller compensates vast amount of reactive power rapidly, and then ARV compensates and reduces it gradually. Finally SVR detects low-voltage and changes its tap position. This method allows the D-SVC to operate with a SVR without the need for a direct communication link [4].

Table 2: Comparison of Voltage Controller

Cont-roller	Block Diagram	Purpose
AVR		To maintain voltage within specific limits
ARV		To suppress long-term fluctuation of voltage
SFV		To suppress short-term fluctuation of voltage

DEMONSTRATION PROJECT

Cornwall, in the southwest of the UK, has recently seen a large increase in PV and wind power generation as it is one of the sunniest and windiest parts of the UK. It is anticipated that these types of DRG will continue to increase in the near future. This region is served by WPD (Western Power Distribution), is mostly rural and thus 11kV distribution feeders are quite long (tens of kilo-meters) and thin, hence their impedances are high. When relatively large-capacity windfarms are connected to these networks, voltage fluctuations on the feeder are amplified and may cause the system voltage to exceed statutory limits.

In this project, a D-SVC was installed on a rural 11kV network to which a windfarm consisting of two 850kW synchronous generators (1,700kW in total) is connected. The aim was to analyse the effectiveness of the D-SVC in controlling voltage fluctuations caused by the windfarm. Figure 3 shows the single line diagram of the distribution system. The windfarm is at the end of the feeder, while consumers are connected at various locations along the feeder between the windfarm and the substation. The D-SVC is installed at the point where the windfarm is connected so as to efficiently control voltage changes caused by the windfarm. For the purpose of the project, measurements are taken from the substation, windfarm, D-SVC and two points (Load1, Load2) along the feeder. Using this system, a function test and a performance test of D-SVC described below are performed.

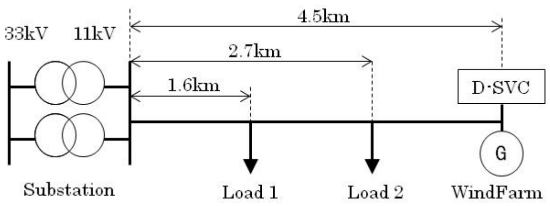


Figure 3: Power system for demonstration project

FUNCTIONAL TEST AND RESULT

During the demonstration project, all three voltage control functions of the D-SVC were tested. As the rated capacity of the D-SVC is only 400kVA compared with 1,700kW of wind power generation, the efficiency of the voltage control is very important, so as to prevent the reactive power output from being saturated. Furthermore, because voltage fluctuation time frames are different for each of the control modes (refer to Table 2), it was necessary to test the effectiveness of each mode with respect to voltage fluctuations on the network.

The voltage change of the network depends on changes in windfarm output and the position and operation of the tap changer in the primary substation along with the load on the network. Therefore, the D-SVC was operated continuously with each voltage control mode for two weeks whilst collecting data at a sample rate of 100ms. Figures 4, 5 and 6 show one of the phase voltages Vc at the point of windfarm, the reactive power Q and voltage Vsvc of D-SVC. These figures also show the calculated phase voltage Vc' when D-SVC is off by using formula (1) with Q, Vsvc, Vc and impedance of distribution system in per unit.

$$V_c' = V_c - X \cdot \frac{Q}{V_{svc}} \qquad (1)$$

AVR Mode

Figure 4 shows the result of AVR mode when the reference voltage is 6,223[V] (0.98[PU]). Overall, Vc is maintained closer to the reference voltage when the D-SVC is on, compared to when the D-SVC is off. When Vc is far from the reference voltage, such as between 100sec and 500sec, the D-SVC outputs maximum reactive power. From thses results, it is confirmed that AVR controller is working correctly. When the deviation of Vc and the reference voltage is approximately 100V (around 700sec), the AVR controller compensates with 400kVAr and reduces voltage fluctuation by 47V which is the best of the three control modes.

ARV Mode

Figure 5 shows the result of ARV mode when moving average time is 10 minutes. At around 2300 sec, ARV mode compensates with 300kVAr and reduces the voltage fluctuation by 40V. Q is then gradually reduced as the voltage returns to "normal". From this result, it is confirmed that the reactive power Q is proportional to the deviation of phase voltage Vc and its moving average. It is also confirmed that the voltage fluctuation with a time frame of less than moving average time is suppressed.

Because the ARV mode performs reactive power compensation only for a specific time frame (10 minutes) the controller outputs Q only for larger voltage fluctuations compared to AVR mode. Therefore, the deviation of Vc and Vc' in ARV mode is smaller than in AVR mode.

SFV Mode

Figure 6 shows the result in SFV mode. When a 310V voltage drop occurs at around 1550 sec, the controller compensates with 400kVAr and reduces the voltage fluctuation to 47V. In the following 10 seconds the system gradually reduces Q output. In this way, the controller prepares for the next voltage drop or surge. SFV mode is effective on networks where voltage fluctuations are caused by, for example, the tower shadow effect of windfarm or where momentary voltage drops are frequent. When voltage changes are moderate, the SFV mode does not perform wasted reactive power compensation.

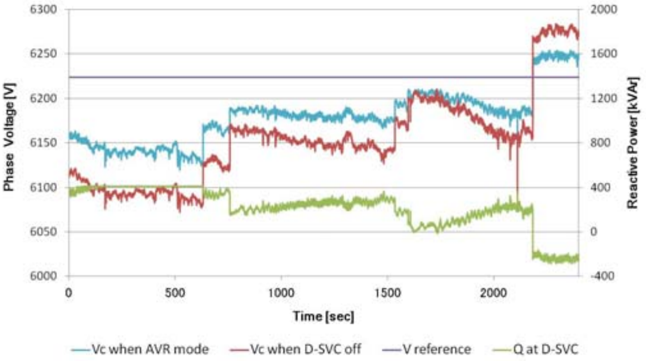


Figure 4: Phase voltage at WF during AVR mode

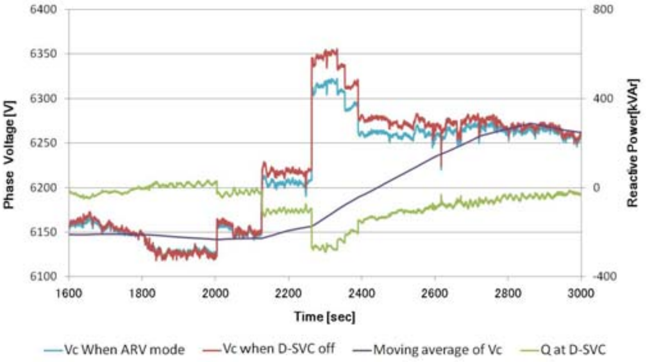


Figure 5: Phase voltage at WF during ARV mode

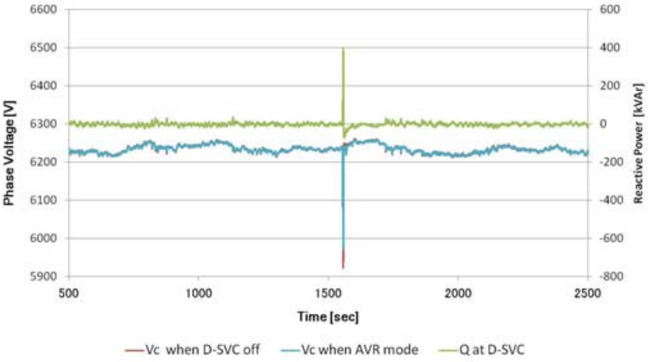


Figure 6: Phase voltage at WF during SFV mode

PERFORMANCE TEST AND RESULT

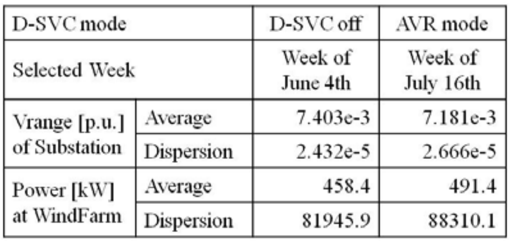
The tests confirm that AVR mode provides the best results out of the three control modes with respect to voltage control.

The maximum phase voltage V_{max} and minimum phase voltage V_{min} were measured every ten minutes at Load1 and Load2 shown in Figure 3 in addition to the voltages at the substation and windfarm for a month. However, under-voltage or over-voltage caused by the windfarm during that time frame was rare. This means that it was not possible to evaluate the impact of the D-SVC on extremes of under-voltage or over-voltage through direct measurement. Furthermore, the voltage at the substation is not constant, so it is not possible to evaluate absolute value of the V_{min} and V_{max} as it is. Instead, voltage band V_{range} of 10 minutes was calculated from formula (2) and are used for the evaluation index.

$$V_{range} = V_{\max} - V_{\min} \qquad (2)$$

The distribution network to which the D-SVC is connected is a production network and it was impossible to find the same network conditions when the D-SVC was switched on and off. Therefore we compared V_{range} over five days on weekdays when conditions (i.e. load and generation) at the substation and windfarm were almost the same. In other words, average and dispersion of Vrange at substation and real power at windfarm for each week are calculated. Then we selected a pair of weeks in which their averages are close and dispersion of AVR mode week is at least worse than one of the D-SVC off weeks (see Table 3). This ensured there was no over estimation of the impact of the D-SVC.

Table 3: Conditions of Substation and WF



D-SVC mode		D-SVC off	AVR mode
Selected Week		Week of June 4th	Week of July 16th
Vrange [p.u.] of Substation	Average	7.403e-3	7.181e-3
	Dispersion	2.432e-5	2.666e-5
Power [kW] at WindFarm	Average	458.4	491.4
	Dispersion	81945.9	88310.1

Figure 7 shows average of V_{range} at the substation and windfarm when the D-SVC is either off or in AVR mode. When the D-SVC is off, V_{range} increases as distance from the substation increases. This is because load changes at Load1, Load2 plus a change in the output of the windfarm result in an amplified voltage change along the line. However, in AVR mode, V_{range} of the substation and the windfarm is almost the same at 0.0072 pu. This means that a voltage fluctuation caused by windfarm (at the windfarm) is suppressed by D-SVC. In addition, at Load2, voltage variation is reduced by around 10%. This relatively small change is because Load2 is nearer the substation than the windfarm, system impedance is small, and thus suppression of voltage change by D-SVC becomes small.

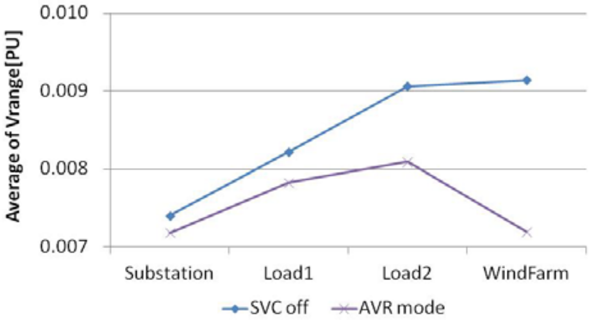


Figure 7: Effectiveness of AVR mode

CONCLUSION AND FUTURE WORKS

The project has confirmed that a D-SVC can control voltage fluctuations caused by a windfarm. Outstanding issues to be addressed include the appropriate sizing of the D-SVC in terms of the generation connected to a network and the voltage variation it causes.

The next step in the project will be to install a D-VQC to provide synchronised control of multiple D-SVCs spread across several 11kV feeders [3][5].

Acknowledgments

We would like to thank the UK government and Ofgem for the establishment of the LCNF, which has enabled vendors, such as Hitachi, to work in partnership with UK DNOs, such as WPD, in trialing new innovative solutions across the UK distribution network. The learning gained from these projects will surely help Great Britain move towards a low carbon economy.

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