A MULTI-OBJECTIVE CONTROL STRATEGY FOR DISTRIBUTION NETWORKS WITH RENEWABLES

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ABSTRACT

When managing low voltage distribution grids with high shares of renewables, there can be several conflicting aims, such as avoiding asset overloading, keeping voltage within set boundaries and maintaining particular active and/or reactive power set points. In the DEMOC project (Distributed Electricity generation with Multi-Objective Control) a control strategy was developed for low voltage networks to reach multiple objectives and, in case of conflict, resolve them according to a given priority weighting. This strategy was then implemented as a software program and tested at the laboratory of the Centre for Renewable Energy Sources and Saving (CRES) in Athens, as part of the EU-supported DERri programme[1]*. Results of the tests are presented here.*

INTRODUCTION

The increase in decentralized generation in the distribution grid, particularly from photovoltaic cells but also from other renewable sources, can cause headaches for network operators. The weather-dependent feed-in adds to the variability already present from the changing load; high feed-in from generation assets can cause over-voltage problems; and network assets which were only ever designed for one-way power flow to loads can become overloaded.

Better coordination of generation, storage and load deployment through information technology is one possible solution to these problems. Here we present a software program that monitors assets within the distribution network and can steer them with set-points for active and reactive power to achieve the objectives of the network operator.

METHODS

At the heart of the system is a software application called the Controller, which was written in the Python programming language to make it portable across a wide range of computer systems. The Controller communicates with the assets, which can include loads, generators and storage devices, using open protocols (OPC in this case). The control logic is represented as a flow chart in Figure 1.

The first task of the Controller is to monitor the voltage, active and reactive power flows and battery states of charge at the different assets and at various points in the network.

Once the Controller has a picture of the state of the network, it must compute set points to send to the controllable assets in the system.

Its first priority is to implement at all times various hard limits, which prevent network equipment from becoming damaged, including:

1. Fixed voltage limits, set for example at ±10% deviation from nominal;
2. Fixed active and reactive power limits to avoid the overloading of network assets, such as generators, cables and transformers;
3. Optionally, the Controller can also prioritize generation from renewable sources.

Within these hard limits, the network operator can give the Controller set points according to a variety of objectives, which the Controller then attempts to reach with the controllable assets it has available. The control modes include:

1. **Voltage control**, in which it steers the assets to maintain voltage on the grid within a set band, e.g. between 0.95 and 1.05 per unit;
2. **Virtual Power Plant (VPP)** mode, in which it aims to provide a set active and reactive power to an external grid connection;
3. **Combined mode**, in which it attempts to reach voltage constraints and VPP set points simultaneously.

In for example [1] local voltage control strategies have been found to be sufficiently robust while also allowing rapid response. Therefore in this project voltage control is done locally at each asset, using first reactive power, then if necessary also active power. In VPP mode the global sums of active and reactive power across the network are regulated.

In combined mode, voltage control and VPP set point objectives may not be simultaneously achievable. For example, a high active power requirement from all generation assets may cause the voltage to rise above the allowed limits.

Therefore when these set points come into conflict, the Controller makes a compromise based on a weighting set by the user as to which goal is more important. The user weights the importance of the objectives with a continuous parameter between 0 and 1, based on which the controller then relaxes the objectives.

[1] Distributed Energy Resources Research Infrastructure, http://www.der-ri.net/.

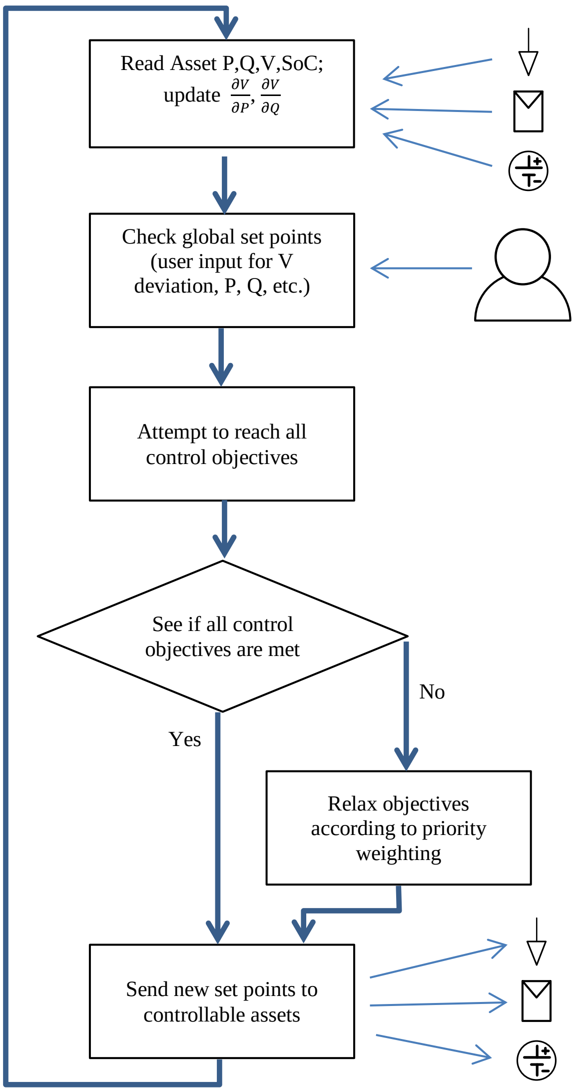

Figure 1 Flow chart of Controller logic

The Controller can monitor the response of the assets to its instructions and adjust its behaviour based on past experience (such as updating its estimates of $\frac{\partial V}{\partial P}$ and $\frac{\partial V}{\partial Q}$ at the measured points). The Controller is also designed to function when there is only partial data from the network.

The Controller was tested on a computer model of a residential distribution grid built in DIgSILENT's PowerFactory and then with a real network at the laboratory of the Centre for Renewable Energy Sources and Saving (CRES) in Athens.

COMPUTER SIMULATION RESULTS

The Controller was tested on a virtual distribution grid consisting of 16 households on two strings (see Figure 2). Each household consists of a load, a PV panel and a storage device. The PV panel has an exogenous uncontrollable active power corresponding to the insolation, while the reactive power can be set by the Controller. The storage assets have controllable active power, within the limits set by the available state of charge at the time.

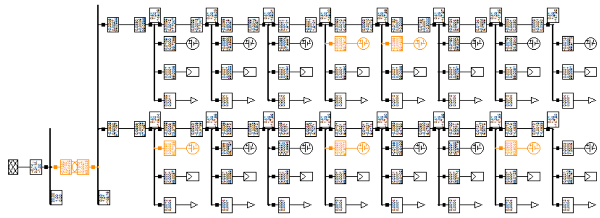

Figure 2 PowerFactory model of residential network

Figure 3 presents the results of an early test of the Controller in voltage control mode, where limits of $0.95 \leq V \leq 1.05$ per unit are set by the network operator. In order to maintain the voltage at each household within the allowed band during times of high PV feed-in, the Controller sets the storage assets to absorb active power, while the PV units themselves absorb reactive power (the time resolution here is low, which is why the profiles are blocky).

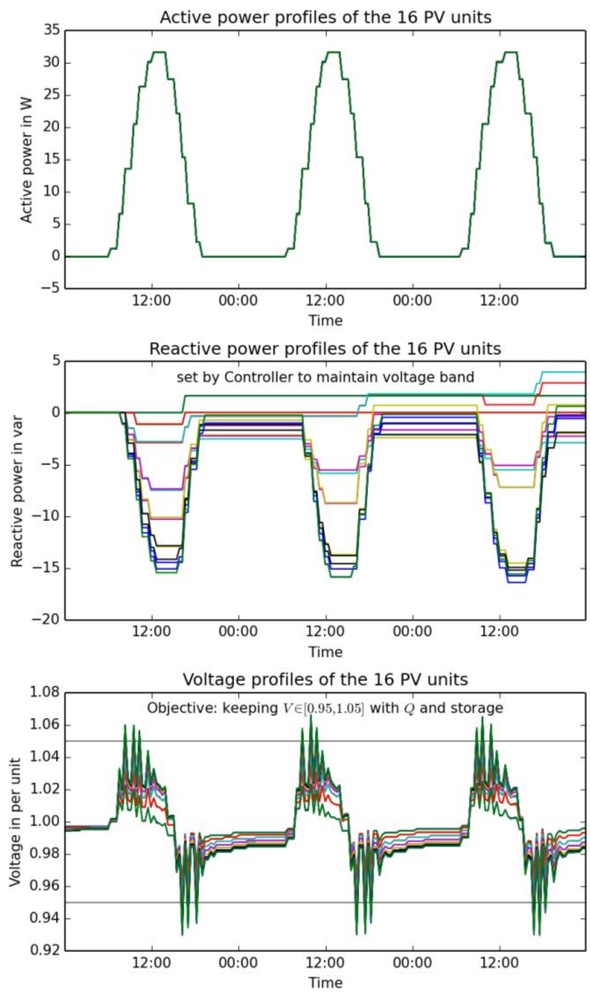

Figure 3 Power and voltage profiles from an early simulation with the residential network's 16 PV units

Already an undesirable interaction between the assets can be seen in the graph of the reactive power: at the same time as PV units far from the grid connection point are absorbing reactive power, the effect on households near the grid connection is to lower the voltage sufficiently that they have to feed in reactive power to compensate. The Controller was subsequently modified to prevent reactive power transfers between assets in the grid like this, which can in general be tricky to control [2]. Similarly, protections are in place to stop storage assets in different parts of the network storing and generating at the same time (i.e. simply transferring energy around the system).
Rigorous tests were carried out for all the Controller's main modes in a variety of situations, with the aim to keep the control logic as simple as possible, while avoiding the negative interactions that arise due to couplings between the assets.

LABORATORY TESTS AND RESULTS

Once the Controller had been successful tested in a variety of computer models, funding was obtained through the Distributed Energy Resources Research Infrastructure (DERri, http://www.der-ri.net/) to test the Controller software with a real grid at CRES on the outskirts of Athens.

Laboratory description and configuration

The laboratory grid was set up to model a residential network on a single phase (see Figure 4) with:

- two PV panels with powers of 2.5 kW and 1.1 kW (peak), no Q control and no continuous P control;
- two battery storage systems connected with SMA Sunny Island inverters, capable of delivering 3.3 kVA each, P and Q steered through f and V droop;
- dummy loads with active power of 4.5 kW (in discrete steps) and a capacitor bank with up to 0.9 kvar, following a typical residential load profile;
- various impedances to insert in the network to simulate long residential distribution lines.

The grid was set up in two different configurations, one with the two PV panels and a single battery, to simulate a single household at the end of a long line, and one configuration including in addition the second battery to represent a second household, separated by an impedance.
Hard limits for the voltage deviation of ±10% from the nominal voltage were set for all assets. This is relevant when the Controller seeks to resolve conflicts between power set points and voltage regulation set points, since in the case of a conflict, the voltage control is relaxed only within the bounds of these global hard limits.
Communication between the assets and the Controller was mediated by an OPC server using the OpenOPC implementation in Python. The Controller has a web-based user interface (see Figure 5) through which the assets can be monitored and set points can be given by the network operator.

Initial set-up tests

Initial tests were carried out to make sure that the assets were able to communicate with the Controller, giving correct readings and receiving and responding to set points. Then the Controller was tested with no extra impedances, to test the simplest Virtual Power Plant mode without the complication of large voltage deviations. During the testing basic consistency checks were made, such as checking that the power flow at the grid connection agreed with the sum of the individual assets.

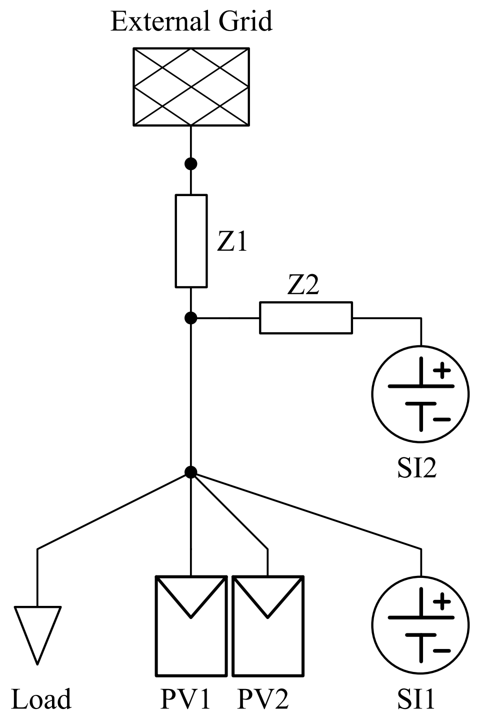

Figure 4 Grid configuration at CRES with both simulated households

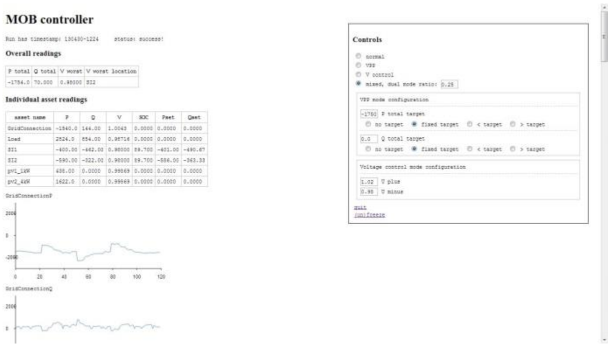

Figure 5 DEMOC Controller in action at CRES laboratory

Single household tests

For the first full test the grid was set up to simulate a single household, following Figure 4 but without the second battery unit SI2. To achieve the voltage drops one would expect to see at the end of a long residential line, an impedance consisting of a resistance of 1 Ω and an inductance of 1.35 mH was inserted between the household and the external grid (Z1). Deviations from nominal voltage of up to 0.08 per unit were then seen with high PV feed-in.

Example readings for a run are shown in Figure 6. In this run two objectives were given equal priority:

- Total reactive power set point of Q = 0 var and total active power set point of P = -1.75 kW, chosen so that the battery would operate both in feed-in and storage mode during the run;
- Maximal voltage deviations from nominal of 2%.

Since the weather was extremely sunny and the skies were clear, the feed-in from the PV panels was relatively smooth and constant. Occasionally the PV panels would trip out and then reconnect, which explains the very sharp spikes in power output.

Therefore the main challenge for the battery to maintain the active power set point was the strongly, discretely varying load. These step changes in the load are the reason for the broader deviations away from the set point that appear in the active power, since the control of the battery active power, steered via frequency droop, took some seconds to react. For most of the rest of the time, the Controller is able to maintain the active power set point very effectively, storing energy during the high PV feed-in and then providing power when the load is high and the insolation is reduced.

When the capacitive reactive load of 0.9 kvar is inactive the Controller is able to maintain the reactive power set point, although at the expense of a voltage slightly below the allowed band. However, when the capacitor bank is active, a conflict arises between the reactive power set point and the voltage target at the SI inverter. This is because if the SI inverter tries to absorb any more reactive power, it will reduced the voltage further, which is already outside the voltage band set by the operator. Therefore the Controller reaches a compromise based on the priority weighting from the operator, reducing the total reactive power to around 0.4 kvar. Beyond a certain point the SI inverter was also not able to respond to the reactive power set points due to the way the Q control via V droop was set up, which had a lower limit for the voltage set point.

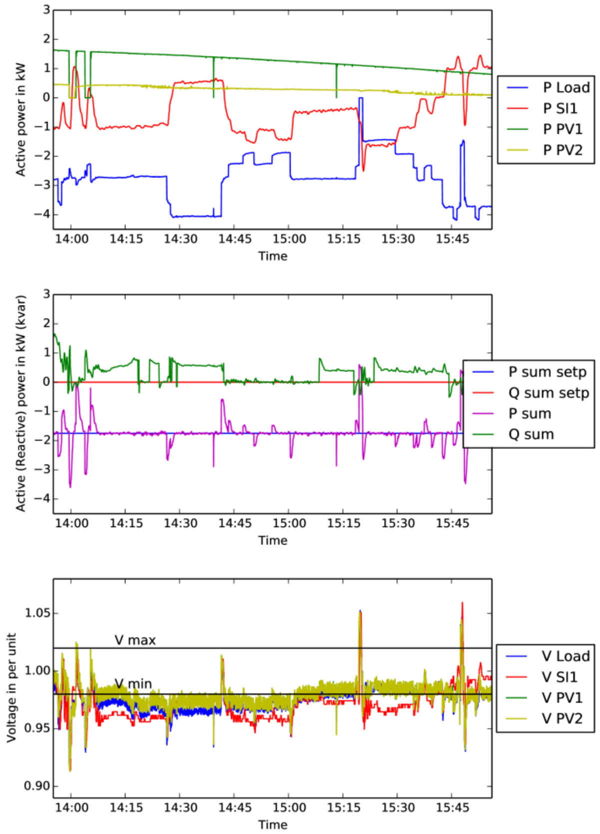

Figure 6 A run in combined voltage control and VPP mode for a single household.

Multi-household tests

For the multi-household test the second battery unit SI2 was included, following Figure 4. The impedance at the grid connection (Z1) was now reduced to 0.5 Ω and 0.9 mH, while the impedance between the second battery unit and the rest of the grid (Z2) was set to 0.5 Ω and 0.45 mH. The total voltage drop for the second battery was now quite substantial, which can be seen later when it was in storage mode.

The run contains examples of three different operation modes, which are marked in Figure 7.

For the first 7 minutes it is given only VPP power set points of P = 1000 W and Q = 0 var. The Controller reaches these set points by putting the batteries into generating mode. The voltage reaches 1.05 per unit but stays within the global upper limit of 1.1 per unit.

For the next 9 minutes the Controller mode is switched to voltage control, with instructions to keep the voltage at all assets within 2% of nominal. The Controller achieves this by reducing reactive and active power at all assets, nearly achieving the voltage band by the time the control mode is switched again.

For the rest of the run, the Controller was given combined objectives of P = –1.75 kW, Q = 0 var and $|V - 1| \leq 0.02$ (the same as in the single household case) but with a priority weighting skewed towards its VPP objectives. Withstanding some reactive power oscillations due to problems with the V droop control, the Controller is able to reach its VPP set points very satisfactorily. The voltage in the first household is also maintained within limits, albeit very close to the lower limit. However, since the second battery (SI2) is bearing much of the burden of absorbing the PV feed-in and it has more impedance between it and the grid connection, the voltage control here is not so effective, and the voltage sinks to 0.96 at times.

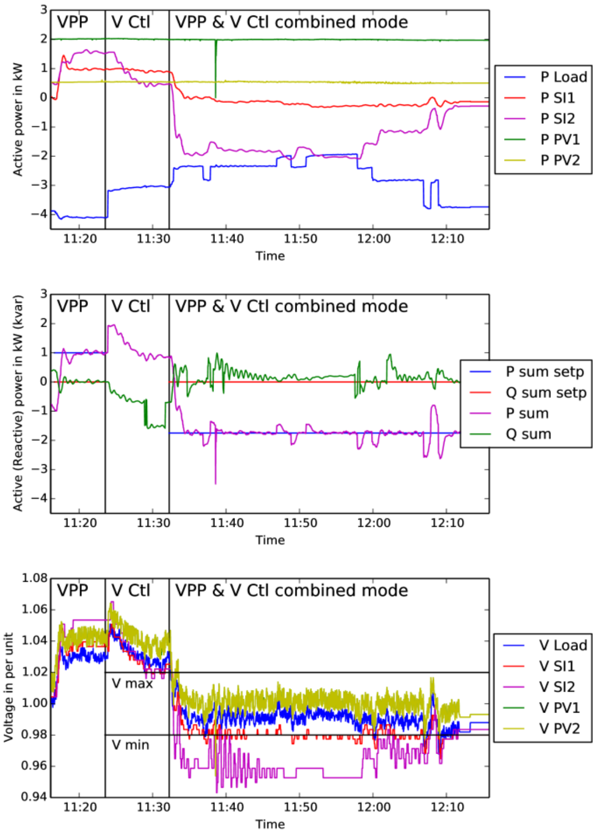

Figure 7 A run in various modes with two households.

The testing of the DEMOC Controller was a success. All test cases were carried out and all minor problems encountered were surmounted. For this very simple system, representing a single household and a two-household network, the controller was able to maintain voltage and keep power set points, within the capabilities of the available assets.

CONCLUSIONS

The DEMOC Controller provides a robust control strategy for distribution grids with high share of renewables, particularly when data is not fully available. It is able to take various set points, such as for power and/or voltage control, and resolve conflicts between objectives according to the priorities of the network operator. We believe that the DEMOC Controller represents the best that can be achieved for a controller that is not explicitly aware of the network topology. It achieves good control with limited information.

The Controller has been successfully tested on virtual residential networks in computer simulations and on a real network in the laboratory at CRES in Greece.

Now that the DEMOC Controller has been tested in real-world conditions, future directions include:

- Multi-agent coordination between many controllers;
- Topology-aware state-estimation to avoid negative voltage control interactions;
- Better optimization to reduce thermal losses in the network, perhaps following the strategy outlined in [3];
- More advanced long-term optimization of the storage state of charge.

We would like to take this opportunity to thank the DERri institutions and our partners at CRES for their support in making the laboratory available and their help making the project a success.

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