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Secondary Control for Microgrids Using Potential Functions: Modeling Issues

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SUMMARY

The power system of the future is an intelligent grid capable of a number of functionalities. These functionalities will enable the power system to exhibit behaviours that enhance the reliability and security of the power system. This modern power system is called the smart grid. In order to ensure proper operation of the smart grid, it is important that its constituent parts operate satisfactorily. An integral part of the smart grid is a microgrid. Therefore, it is necessary that a control strategy for the microgrid in both grid-connected and islanded modes be devised. In this paper, a method for secondary control of microgrids is proposed to ensure their long-term stable operation under various load conditions and different configurations. In this method, a potential function is defined for each controllable entity of the microgrid, and a central controller devises the set of set points that optimize the overall operation of the microgrid.

KEYWORDS

Distributed generation, microgrid, modeling, potential function, secondary control, smart grid.

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1. INTRODUCTION

Power system, the top engineering achievement of the twentieth century, is experiencing a major shift in its operation. Most of the existing power system was designed when lighting of streets and homes was the main purpose of electricity. The current power system, however, plays an important role in a wide range of applications such as communication, financial transactions, transportation, and manufacturing. Such applications require the power system to guarantee a high level of service reliability, which cannot be achieved by mere modernization of the grid infrastructure. Instead, the *smart grid* [1], the vision of the future power system, necessitates a paradigm in which the power system has functionalities such as self-healing, resistance to attacks, active participation of consumers, high efficiency, high power quality, and accommodating available generation options [2]. Several technologies need to be implemented in the smart grid to assist it in achieving these functions. Among them are advanced control methods, advanced components, communications, and improved decision support systems. Since a microgrid is an enabling component of smart grid, this paper, exploiting the first three mentioned technologies, proposes a secondary control method for a microgrid.

The current technical literature on the control of microgrids addresses set point tracking in the grid-connected mode, the islanded mode, and the transition between these two modes [3]-[5]. This does not generally guarantee long-term stable operation of the microgrid. Therefore, there is a need to develop algorithms to calculate optimal set points for the DER units, which are determined from the status of microgrid, the loads and units that are in service, and the market conditions. This paper addresses this need and (i) develops a secondary control method for a microgrid and (ii) proposes application of potential functions for secondary control.

In the proposed potential function based method, the central controller defines a potential function [6] for each DER units in the microgrid. Using the measurements taken at the DER unit and communicated to the central controller, the potential function encodes information about the DER units and their set points. Such measurements could include the terminal voltage, output current, and real and reactive power injection of the DER unit. Each individual potential function is defined in such a way that its minimum corresponds to the control objective of the respective DER unit.

Potential functions provide a concise method for conveying information about the status of the microgrid. The advantages of use of potential functions over the traditional secondary control methods include ease of implementation, their open structure enabling inclusion of additional terms representative of system performance parameters, and provisions for frequency control.

Secondary control is inherently designed to be slower than primary control so that (i) its operation does not interfere with the primary controllers, and (ii) it only requires a low-bandwidth communication link between the system components. Therefore, this work implements the secondary control in discrete time.

This paper also briefly discusses the discrete-time modeling approach. The model enables systematic parameter selection.

2. REVIEW OF MICROGRID CONTROL METHODS

Fig. 1 shows the schematic diagram of a generic microgrid. The microgrid is connected to the main grid at the point of common coupling (PCC). The DG units of the microgrid can in general have any arbitrary configuration. Each DG unit is electronically interfaced to the microgrid through a voltage-sourced converter (VSC). Since the electronic interface is fast, it helps implement the control strategies pertaining to the microgrid.

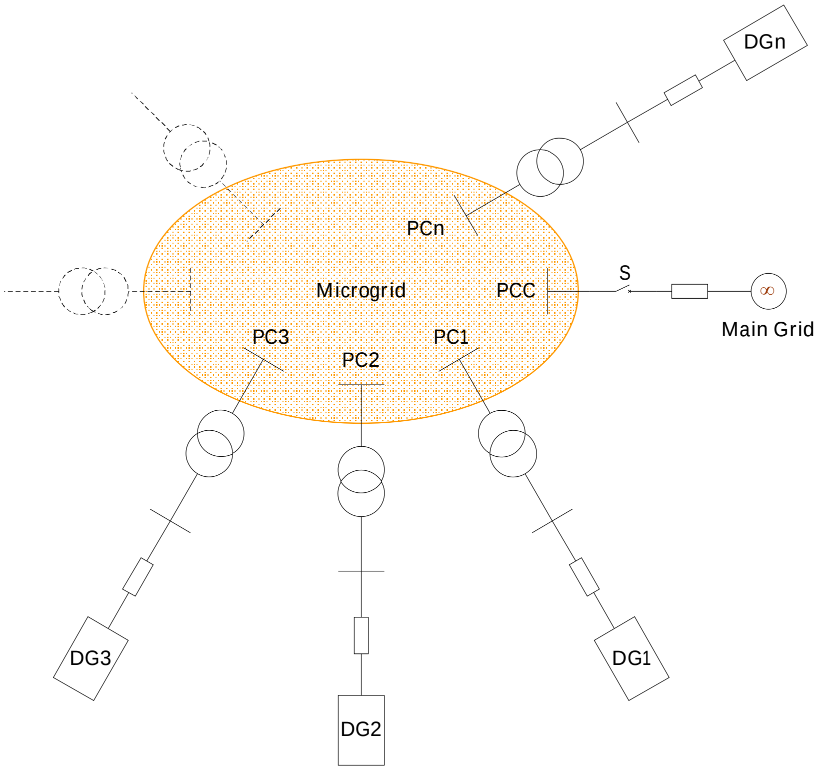

Figure 1. A generic microgrid

A. Droop Control

One control method for a microgrid with multiple DG units is the conventional droop method, Fig. 2. In a synchronous generator, energy conservation implies that

$$P_G - P_L = J\dot{\omega},$$

where P_G is the generated real power, P_L is the load power, J is the system inertia, and ω is the frequency. When the total generated power is more than the required power, the system frequency increases ($\omega > \omega_{nom}$). The control loop of the synchronous generator senses this and reduces the generated power. On the other hand, when the generated power is short of the required power, the system frequency decreases ($\omega > \omega_{nom}$). This time, the control loop of the synchronous generator increases the generated power to counteract this and return the frequency to the rated value.

In the droop control method, each VSC is controlled similar to a synchronous generator by equipping it with two artificial droop characteristics. One droop characteristic controls the voltage magnitude by adjusting the generated reactive power. The other droop characteristic controls the frequency by adjusting the generated real power.

The droop control method has several advantages: (i) it does not need a communication channel, instead, the frequency (or the voltage magnitude) measurement indicates the overall shortfall of real and/or reactive power within the microgrid; and (ii) no coordination is necessary, the units can automatically adjust their set points to meet the overall need of the microgrid in a plug-and-play fashion.

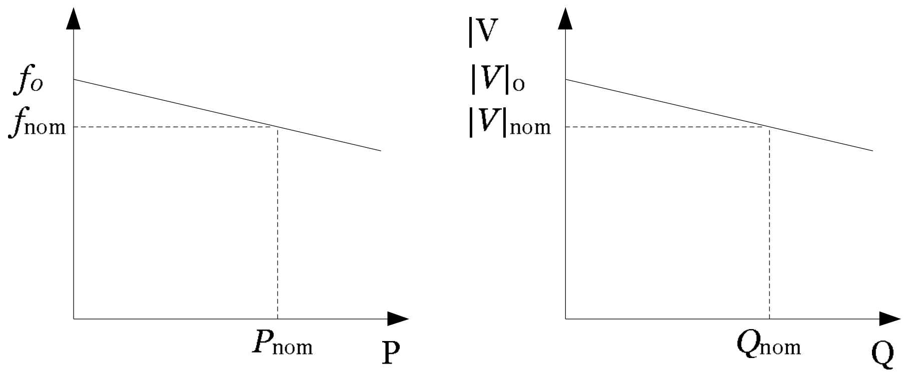

Figure 2. Droop control

The disadvantages of the droop method are

(i) The droop method suffers from a poor transient response. The frequency and/or voltage restoration mechanisms are intentionally slow so that they do not interfere with the droop behavior. This results in a poor voltage regulation in favor of power sharing.

(ii) There is no control over harmonic current sharing, which is dependent on the converter output impedance.

B. Centralized Control

Another approach for microgrid control is centralized control [7]. In this approach, the load current is divided among the DG units according to their power ratings. This method relies on critical communication. The central controller should be aware of the number of units and loads in the system and their models. In the literature, centralized control is studied for the case that the load is aggregated at a single connection point.

These requirements make the controller overly complex. In such a design, the availability of the central controller is crucial to the operation of the whole system, making the central controller a possible single point of failure. Moreover, in a microgrid the topology of the system is very likely to change from time to time. This time dependency of the structure of microgrid further renders its central control a difficult task. In addition, not all control actions need to be performed centrally. For example, while the control of real and reactive power set points is performed centrally, voltage regulation is not performed centrally.

The challenges mentioned above bring about the idea of a hybrid approach using emerging control techniques, which with appropriate coordination can be used regardless of connection type of the DER units

3. THE PROPOSED CONTROL METHOD

This paper proposes implementing a secondary control strategy for a microgrid [8]. Secondary control ensures that the set points of the microgrid conform to the optimality requirement of the microgrid and are based on the appropriate operating points of the DG and DS units.

In this paper, the notion of potential functions is used for the secondary control. A potential function is defined for each controllable unit of the microgrid. This function formulates the characteristics of the system such that minimization of the potential function leads to the desired performance. An example potential function can include terms representing real and reactive power deviation, current exchange between units, and voltage deviation:

$$\Phi = \omega_1 (v - v_{set})^2 + \omega_2 (i_{tie}),$$

where ω_1 and ω_2 are weight factors. The potential function can also include terms representing power flow in a region and proximity terms imposing a flat voltage profile.

A central controller is used to minimize the potential functions. The term PFM, short for potential function minimizer, is coined to refer to this controller. The PFM inputs the required measurements (which will be available as mandated by the smart grid vision) and finds the set points that optimize the system performance for the next time step, Fig. 3. The optimal set points are obtained using a gradient descent method.

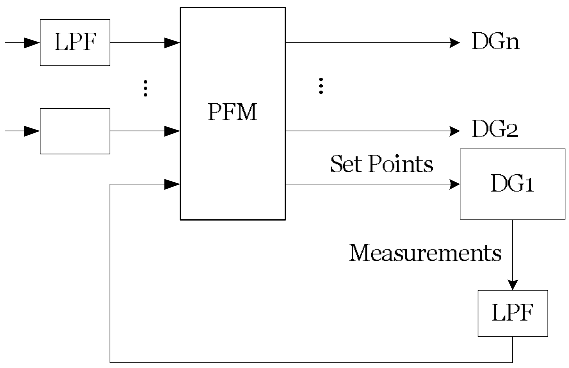

Figure 3. Potential function minimzer

4. INTRODUCTION TO THE MODELS USED FOR SECONDARY CONTROL

The system is assumed to be balanced and is modeled in the *dq*-frame. Since the secondary control is intentionally implemented as a slow controller, it can be implemented as a discrete-time controller in which the system measurements are fed to the PFM at pre-specified instances, and the set points are also updated at pre-specified instances.

The models are also developed in the discrete-time domain using the backward Euler method and an appropriate hold model. Fast transients of the system are ignored for the secondary control since they are mitigated by the primary, local controllers. Therefore, similar to transient stability studies, it is sufficient to represent the network in phasor representation instead of an exact representation using differential equations. This implies that for the secondary control purposes, the microgrid PCs are at constant phase shifts with each other. As such, the model of each DG unit at its PC is transferred to a global frame using the constant phase shift PCs as obtained by load flow.

5. SIMULATION RESULTS

To assess its performance, the proposed control method is applied to a test network. The network used, Fig. 4, is a modified version of the feeder 2 of the CIGRE North American medium voltage benchmark system for network interconnection of renewable and distributed energy resources [9]. Three DG units are installed at the buses 12, 13, and 14 (1, 2, and 3 in Fig. 4) of the feeder. Single-phase loads are disconnected. Since the grid in the benchmark system is very strong, it is not possible to perform voltage control in the grid-connected mode. Therefore, both case studies are performed for the islanded mode of the microgrid. In these simulations, the line 12-13 is out of operation; therefore, the actual system consists only of the DG units 2 and 3 and the associated local loads.

The potential function minimizer measures the voltages at buses 2 and 3 and outputs appropriate set points for the direct and quadrature components of the voltage set point. Two case studies are considered: In the first case study, the voltage level of the microgrid is changed in a step and the transients in voltages and power flows are considered; in the second, the load is changed.

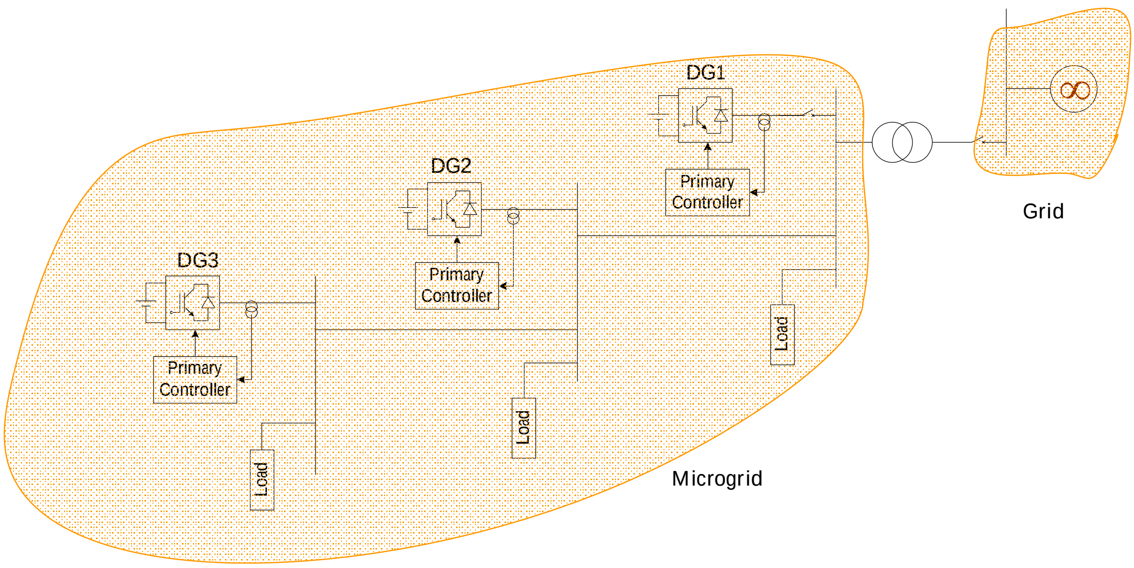

Figure 4. The microgrid of case study

A. Case Study 1: Voltage Set Point Change

In this case study, the voltage set point is changed in a step from 1 pu to 0.7 pu. Although not a practical change in the voltage magnitude, this is used to produce magnified results and assess the applicability of the proposed control method in an extreme case.

Fig. 5 shows the voltages at PC2 and PC3. The secondary controller simultaneously decreases the voltage references for the units DG2 and DG3 in successive steps. The reason the voltage set points of the DG units are not changed instantaneously is to account for slow transients and slow phenomena, e.g., connection/disconnection of loads and change in the active DG units. The timing and magnitude of steps are controlled by the parameters of the potential function minimizer.

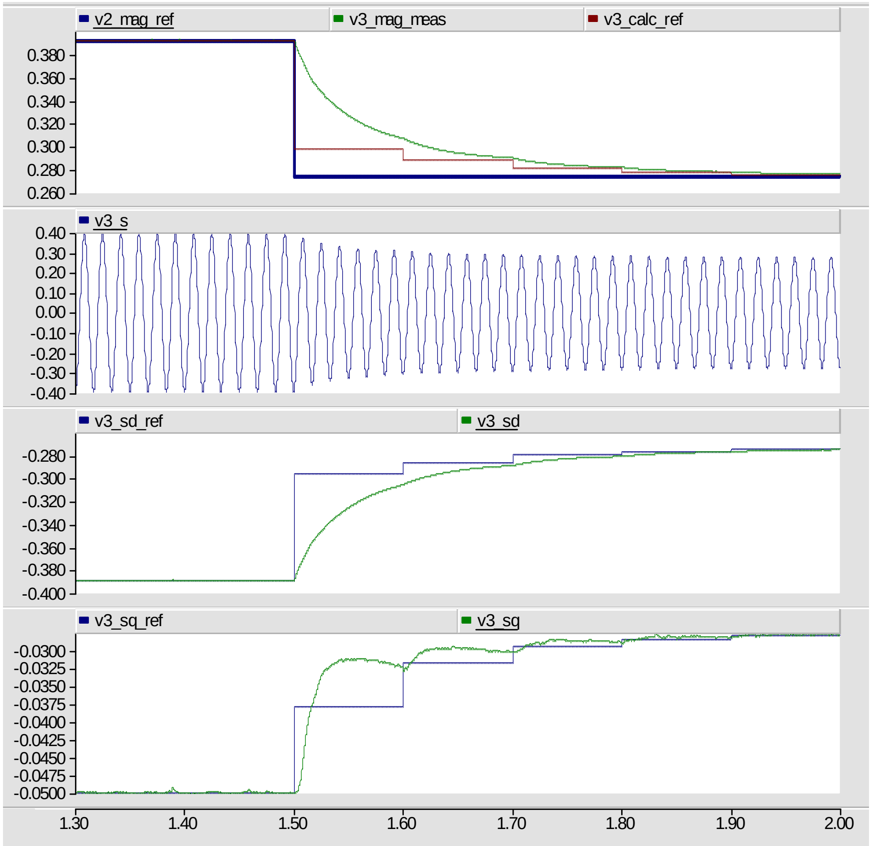

Figure 5. Case study 1: The microgrid response (voltages) to a step change in voltage

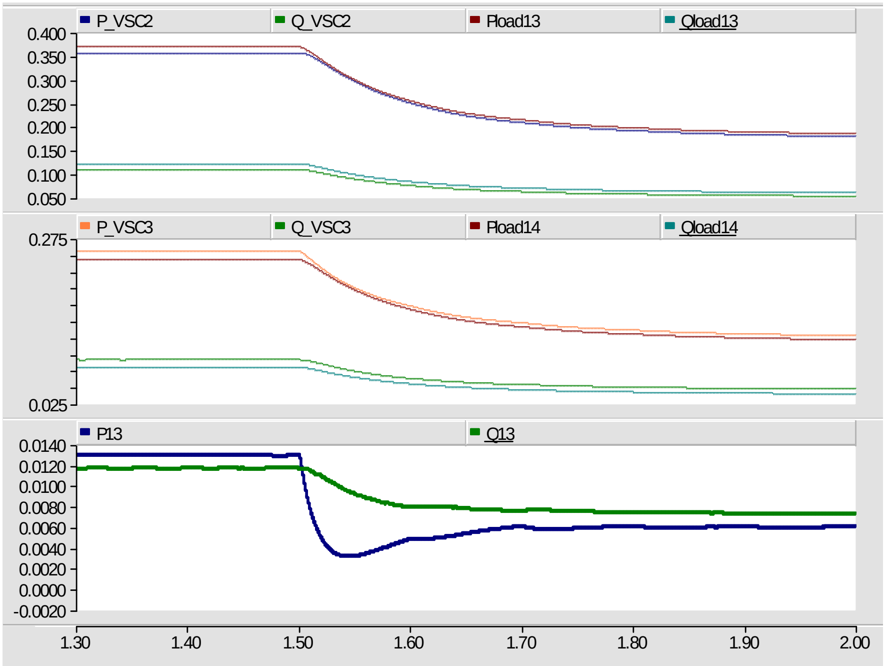

Figure 6. Case study 1: The microgrid response (power flows) to a step change in voltage

As shown in Fig. 5, the voltages (magnitude and both *d*- and *q*-component of voltage) reach steady state in 500 ms, which conforms to the requirement of the secondary control. The voltages at PCs are sinusoidal both before and after the step change.

Fig. 6 shows the real and reactive power flows. Since it is assumed that loads are linear, decreasing the PC voltages also decreases the power delivered to the loads. The mismatch between the real and reactive power generated by DG2 (and DG3) and the real and reactive power delivered to its load is due to different electrical parameters of the DG units and their filters. This in turn causes a power flow in the lines. Because of this, the decrease in the voltage also decreases the current flow in the tie line and hence, the reactive power of the tie line.

This case study confirms the ability of the proposed control method in changing the voltage set point.

B. Case Study 2: Load Change

In the second case study, the real component of the load at PC3 is increased in a step by 10% while the voltage set points are kept constant. Fig. 7 shows the voltages subsequent to this disturbance.

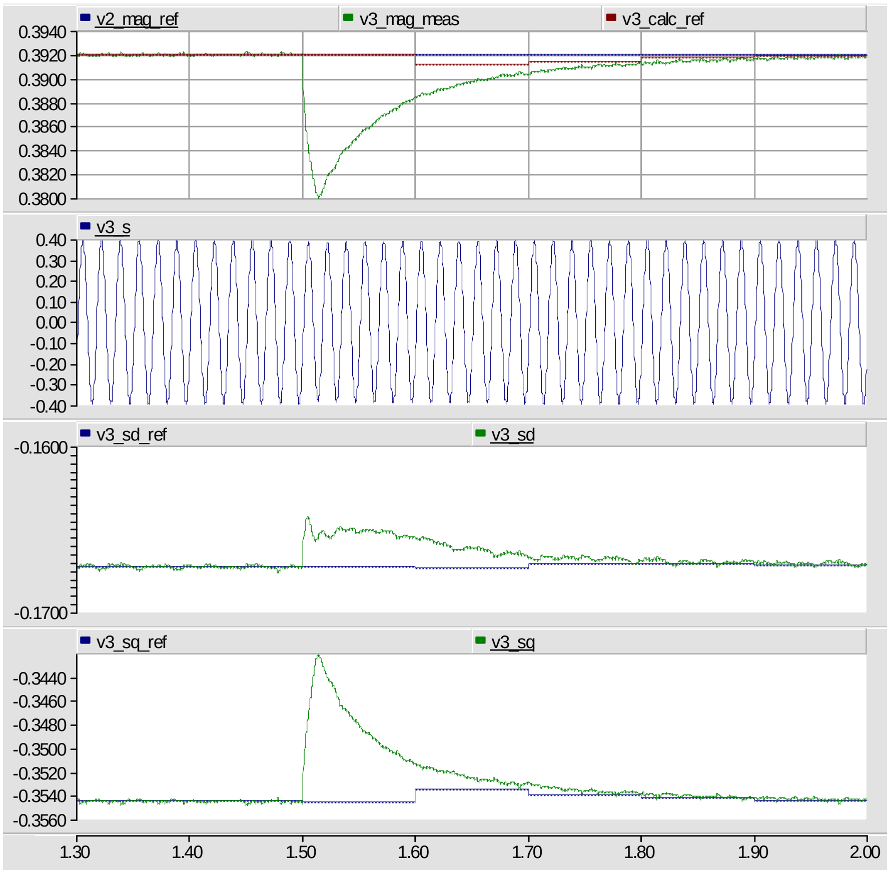

Figure 7. Case study 2: Change of load

Immediately after the disturbance, because of the increased load and hence, current flow in line, the voltage at PC3 decreases by less than 5%. The PFM slightly adjusts the voltage set point so that the power flow between the DG units is controlled. The PFM's operation occurs with a delay, because it only responds to disturbances at pre-specified time instants to prevent interaction with the local controllers.

The system recovers in 500 ms and stays stable after this disturbance. This case study confirms robustness of the proposed control strategy.

6. CONCLUSIONS

This paper introduced the concept of the potential function based secondary control for a microgrid. In this method, a potential function is defined for each DER unit in the microgrid. A potential function conveys information about voltage, current, and real and reactive power of each DER unit. The potential function also summarizes the constraints of the DER unit and its control target. A central controller, potential function minimizer, uses the gradient descent method to find the set points that result in the minimum of each potential function. Such set points are communicated back to the DER units.

The concept is evaluated based on the system performance in a case study whose goal is to control the voltage of the points of connection of the microgrid DG units. It is shown that the system response to major types of disturbances reaches steady state within the allowable time.

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