Secondary Control in AC Microgrids
Challenges and Solutions

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Abstract: The hierarchical control structure of a microgrid can be described as consisting of four levels: processing, sensing and adjusting, monitoring and supervising, and maintenance and optimizing. This paper focuses on the secondary control level, which can be classified as centralized or decentralized control. A comprehensive investigation of both centralized and decentralized control is presented in this paper. Decentralized control is proposed in order to deal with some of the disadvantages of central control, such as the high risk of unplanned interruption arising from a Microgrid Central Controller (MGCC) malfunction. However, decentralized control is not yet complete, and some challenges to its implementation remain. This paper also looks at these challenges and proposes some solutions that may help to improve the performance of decentralized control and overcome its disadvantages. Finally, a general methodology of microgrid control is modeled.

1 INTRODUCTION

In previous decades, fossil fuels were the basic resource for generating energy in the world. However, taking into account the increasing costs of energy and the associated environmental concerns, industrial experts and researchers are presently seeking to replace fossil sources by Renewable Energy Sources (RESs). In this regard, the European Union (EU) has established the so-called 20-20-20 energy target, which requires a 20% decrease in greenhouse gas release, a 20% increase in the consumption of energy from RESs, and a 20% decrease in primary energy consumption through improvements in power efficiency by 2020. Moreover, based on the energy roadmap for 2050, which aims for a 41% decrease in energy demand through increases in energy efficiency, the role of RESs will be more significant in future (Lise, van der Laan et al. 2013).

To solve the problem and to increase both efficiency and power quality, RESs can now be integrated into the main network in the form of Distributed Generators (DG) or Microgrids (MG). A MG consists of a methodical organization of such DG systems—an organization that leads to increases in system capacity and achieves the aimed-for high power quality (Li and Kao 2009). Moreover, the Energy Storage System (ESS) is an important component of the microgrid, which satisfies requirements in many instances, such as ancillary services like load following, operational reserve, frequency regulation, peak shaving, black start during island mode, renewable integration, and relieving congestion and constraints.

Controlling the DGs and MGs is a critical topic, and it is necessary to implement a hierarchical control system in order to achieve this. A comprehensive analysis of hierarchical microgrid control, applying the IEC/ISO 62264 standard, is presented in (Palizban, Kauhaniemi et al. 2014; Palizban, Kauhaniemi et al. 2014). Based on the microgrid control scheme proposed in those papers, hierarchical control consists of four different levels. There are many different technical possibilities for each of the control levels. A complete review of primary techniques is presented in (Vandoorn, De Kooning et al. 2013). Based on the secondary control level, which is investigated in (Guerrero, Vasquez et al. 2011; Shafiee, Guerrero et al. 2014), control levels can be classified into two types: *centralized* and *decentralized*. The definition of (de)centralization is based on the position of the MGCC. A significant disadvantage of the centralized method is that the system will go completely out of service if any problem occurs in the MGCC. To overcome this drawback, a

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decentralized control method has been proposed, but this cannot support the system in all its function. In this regard, the present paper investigates the challenges to microgrids using decentralized secondary control, and introduces some solutions to deal with the disadvantages. This paper is organized as follows: a preliminary discussion of hierarchical control is presented in Section 2. Section 3 discusses secondary control in detail. Hierarchical control of ESS is presented in Section 4. The challenges and solution to secondary control are described in Section 5; in Section 6, a general hierarchical control in microgrid is modeled. Finally, the paper is concluded in Section 7.

2 HIERARCHICAL CONTROL LEVELS

The principle of the classification of the control levels in MGs is shown in Fig. 1.The hierarchical control structure of MGs can be classified into four levels, which are explained as below:
The source operating point control is the first step in MG control, and is designed using power electronic devices. Generally, the control level is achieved through the inner current and voltage control loop, and the main goal of this control level is to manage the output power of the micro sources (MSs). In the next control level the primary control accounts for any variation in the system on the order of milliseconds, so the fastest response is provided by this primary control. The aim of this control level is to adjust the reference values from the amplitude of the voltage and the frequency in order to feed the inner control loop. Supervising and monitoring the frequency and voltage is the main duty of the secondary control level. In fact, during any variation in load or generation in the MG, the secondary control regulates the deviation in the appropriate limitation range—for example, by ± 0.1 Hz in Nordel (North of Europe) or by ± 0.2 Hz in UCTE (Continental Europe) (Guerrero, Vasquez et al. 2011). Compared to the primary control level, the secondary control has a slower dynamic response to variation. This control level can be classified into centralized and decentralized controls, which are discussed in depth in Section 3. In the last, the third control level is the final and slowest. It regulates the frequency and voltage when the MG is connected to the main grid. This adjustment is based on measuring the active and reactive power from the main grid.

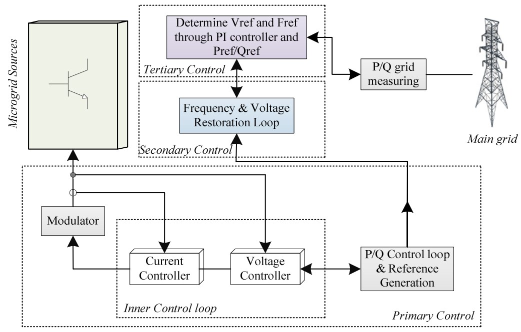

Figure 1: The hierarchical control structure of MGs.

3 SECONDARY CONTROL

As mentioned previously, centralized, and decentralized control are methods of secondary control for adjusting the output of each different DG. The principle of centralized control methods in MGs is very similar to in the inner control loop. The MGCC plays the main role in managing the power between the different DGs and interfaces with main grid (Fig.2).

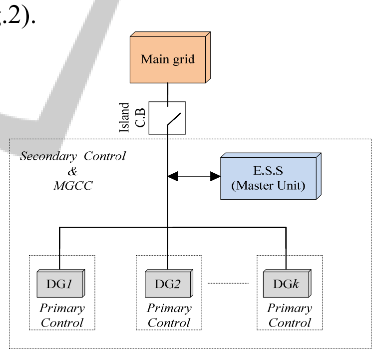

Figure 2: The principle of centralized control methods in MGs.

The MGCC detects all the values from the main grid and DGs, and provides a reference value to send to the primary and inner control loops. Fig.3 illustrates the processing of the secondary control level in the central method.

The significant disadvantage of this method is the dependence of the control on MGCC, which means that the system faces a problem when there is any malfunction in the central control. Moreover, a communications link between all DGs and MGCC is required for centralized mode, making the method more unreliable (Bidram, Davoudi et al. 2013). To overcome these problems, distributed secondary control has recently been proposed in(Shafiee, Vasquez et al. 2012; Bidram, Davoudi et al. 2013; Bidram, Davoudi et al. 2013; Shafiee, Guerrero et al. 2014).

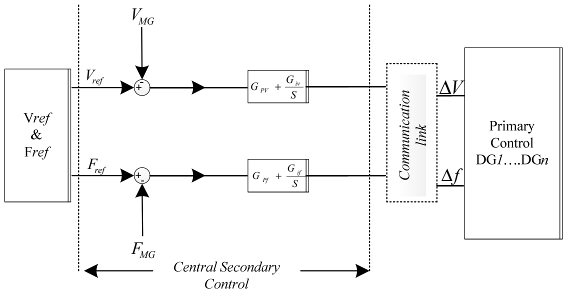

Figure 3: The secondary control level in the central method.

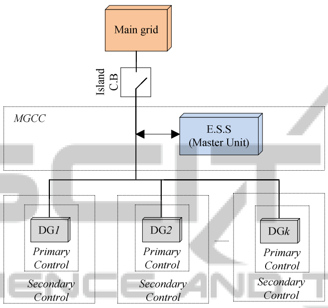

Figure 4: The principle of decentralized control methods in MGs.

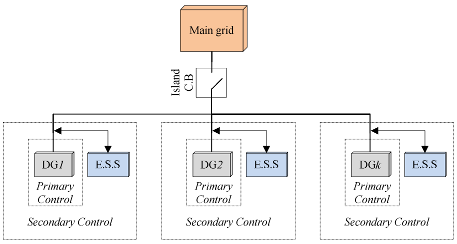

Figure 5: combining the decentralized control for the DGs and ESS.

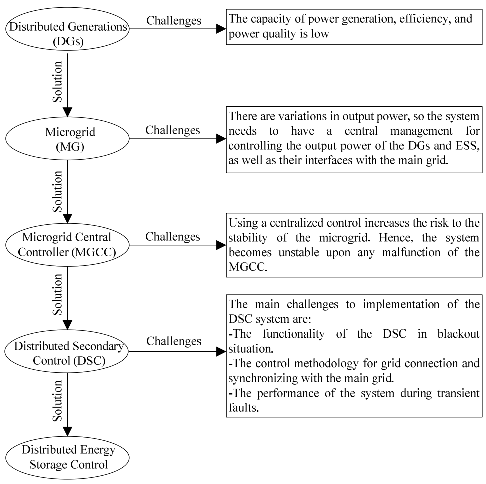

Figure 6: A chart of the challenges and solutions.

The duty of the control in the second level, whether it is centralized or decentralized, is almost the same, though there are some differences between the operating types.

In the decentralized set-up, the MGCC for controlling and supporting the primary control has been removed and the secondary control is transferred to beside each primary control (Fig.4). In centralized control, the output voltage of each DG is measured using remote sensing and is sent to the MGCC, while in decentralized control, the sensing and measurement of the voltage is performed at the terminal of each DG unit.

4 HIERARCHICAL CONTROL OF ENERGY STORAGE SYSTEM

As illustrated later in Section 6**,** the DGs units have either some delayed response or slow controllability to variation inside the MG. Hence, it is necessary to cover the gap during island mode using ESS. The system is managed by charging and discharging the ESS. Hierarchical control of ESS is included in two levels: primary and secondary. The third control level in ESS is the removal of the storage control, because the energy storage is a local resource and does not cooperate with the main grid. The voltage and the frequency of the MG are adjusted though the ESS primary control. As presented in (Loh and Blaabjerg 2011), the frequency of the system (f) is used to measure the microgrid's capacity. Based on this sensing, if the frequency of the network is near to the maximum value (f_{max}), then the power generation is higher than the power demand, so the energy storage system must absorb the additional energy and remain in charging power mode throughout its current state of charge (SoC). A frequency that lies between the maximum and minimum value is a normal situation that does not need energy to be absorbed or injected by the energy storage system. However, if the frequency drops close to the minimum value (f_{min}), this means that the power demand has increased and that the energy storage system should inject stored power and move from charging mode to discharging mode. However, since the energy capacity of the energy storage is limited, the output power of the ESS must return back to zero or some other fixed value needed to maintain the SoC with the increasing output power of the DGs. Decreasing the power is the duty of the secondary control level of the energy storage system (Kim, Jeon et al. 2010). As described in Section 2, increasing the output power from the DGs is the responsibility of the primary control level.

5 CHALLENGES AND SOLUTIONS

As described above, the responsibility of secondary control is to support the MG in achieving reliable output from the different DGs. The control level modeled in the next section is based on a general approach to a central control for MGs. Based on the results of this model, a centralized control method is proposed to manage the output power from DGs; however, their response time is not fast enough, and it is necessary to add some ancillary service to cover the delay time. The ESS is the best solution for a fast response to cover the delay. Power management and the balancing power between DGs and ESS is also the duty of the MGCC. One challenge to centralized control that might prevent the system operating at the optimum level with high efficiency and good performance is the high risk to system stability. Fig.6 presents a chart of the challenges and solutions. The decentralized control is proposed for improving performance and enhancing the efficiency of the system. Although this control type can help in removing the MGCC from the microgrid, there are some challenges to implementing the control strategy—such as operating the microgrid using a distributed control strategy during grid connection mode and the synchronization process between DGs and the main grid. Indeed, most studies of this control method have focused on the island mode. Moreover, The inability of controlling the system during the transient and persistent faults that cause blackout situations in microgrids (as well as black-start coordination) without an MGCC and some of the other management functions of the MG are challenges to implementing a fully decentralized control system (Shafiee, Guerrero et al. 2014). One way of dealing with these challenges and achieving a greater level of control in practice is to use a distributed energy storage system, which would be installed beside each DG. Based on the structure of the system (see Fig.5), the arrangement consists of a set of DGs with storage, along with separate primary and secondary controls. Although a distributed energy storage system has recently been proposed by (Morstyn, Hredzak et al. 2014; Xu, Zhang et al. 2015), however in these studies, only the possibilities of this system is investigated whereas MGs are controlled centrally. The benefit of combining the decentralized control for the DGs and ESS is that it may help increase the efficiency of the decentralized secondary control, by solving the previous problems of this control level, as well as increasing the power reliability by decreasing the error rate and the number of unplanned interruptions of the system, controlling the system during transient faults and coordinating the system in black-start situations. Finally, the faster response and easier energy management in island mode will also assist in critical situations.

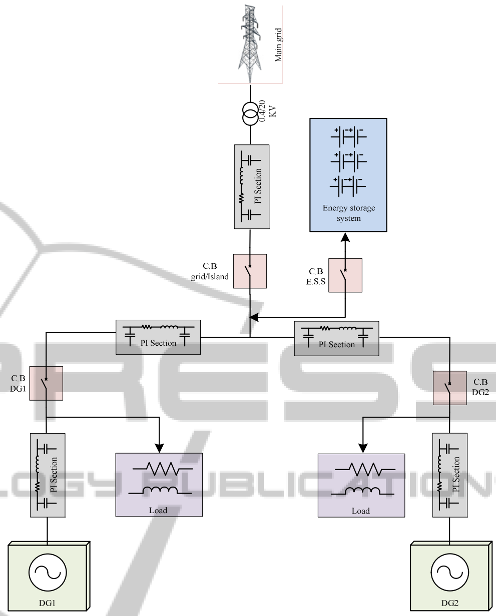

Figure 7: The structure of the simulation case study.

6 MODELING OF HIERARCHICAL CONTROL

The regulation of voltage and frequency in hierarchical control, as described in Section 2, is modeled in this section on the basis of the general approach presented recently in many papers. In the simulation, the centralized secondary control was utilized, and some parts from models previously created in joint projects between the University of Vaasa, VTT, and ABB were employed. The network examined in this paper is shown in Fig.7.

It consists of a transformer (MV/LV) with an 800 kVA capability and a circuit breaker (CB) controlled by the MGCC. During the simulation, the islanded microgrid is disconnected from the main grid by this breaker. The inverter-based DGs operate on the basis of active and reactive power control in grid connection mode, and on the basis of voltage and frequency control mode during island mode. Fig.8 shows the control-block diagram modeled in PSCAD. The results obtained from the dynamic system study are as follows: To investigate the system in both modes, the system was connected to

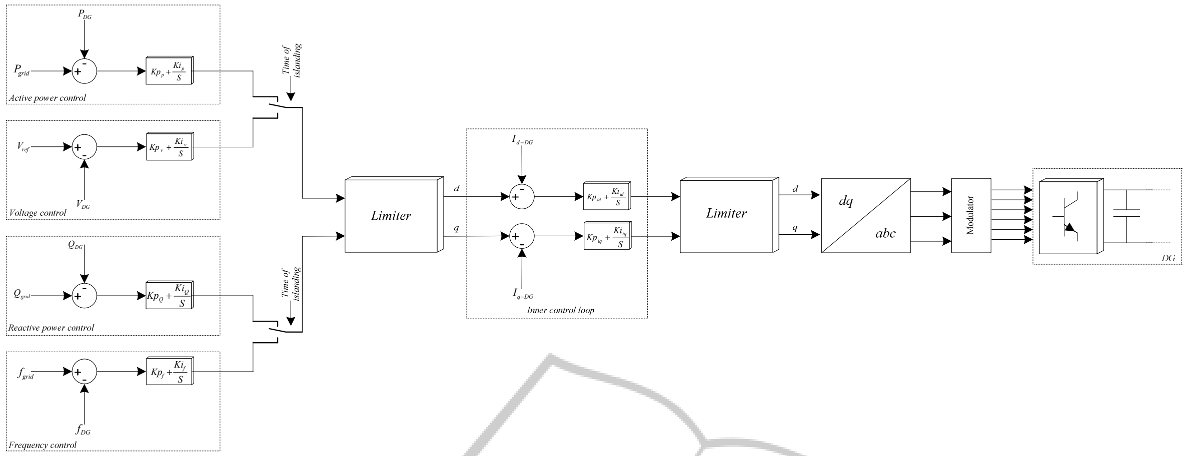

Figure 8: The Control block diagram of the MGs in the grid connection and island mode.

the main grid at the beginning of the simulation and disconnected after 4 seconds. The system did, in fact, operate in island mode for the rest of the running time.

The voltage on the LV side of the transformer is shown in Figure 9**.** After the isolation of the system from the main grid, power balancing became the responsibility of the energy storage system However, since this paper investigates only centralized and decentralized secondary control, the storage system result is not described here. The output voltage, current and active power of the DGs is presented in figures 10, 11, and 12, respectively. The slow response of DGs for needed power increase, which constitutes a challenge to supporting the system, can be seen clearly in Fig.12. DGs are not able to increase the power output immediately when the system is disconnected from grid and is operating in island mode. Since the simplified model applied here does not consider the power increase rate limits of the primary energy source the problem will be even bigger in practical system. In frequency control part, Fig. 13 shows the frequency of DGs during grid connection and island mode.

7 CONCLUSIONS

Based on the hierarchical control strategy—an important feature of microgrid operation—this paper focuses on the secondary control, which can operate on the basis of centralized and decentralized control. The challenges to the complete implementation of secondary control are discussed in this paper. Of these, the challenge of coordinating the control level during black-start situations is the most important. Based on this study, a combination of distributed energy storage and the MG, which is controlled by a decentralized secondary control, may help overcome these implementation challenges. It is expected that these solutions will improve efficiency, power reliability, and response time, while decreasing lost power and the error rate of the system. The investigations so far are technical in nature; research into the economic aspects of this arrangement is thus a key question for future work.

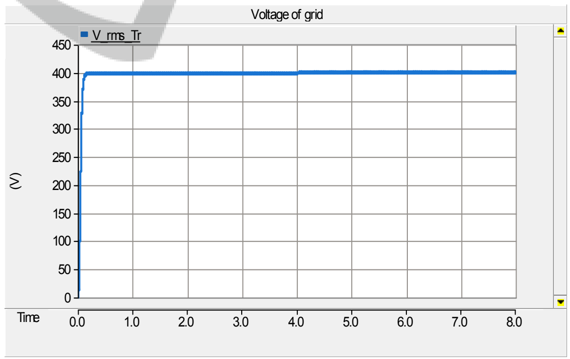

Figure 9: The voltage on the LV side of the transformer.

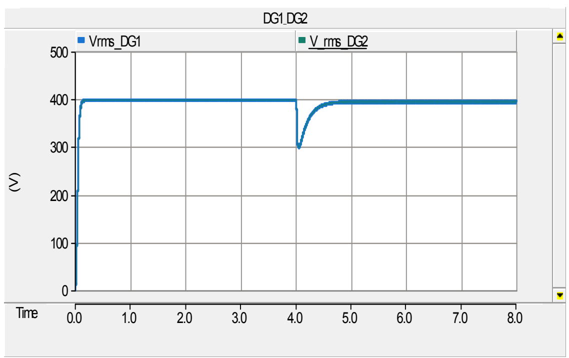

Figure 10: The output voltage of each DG.

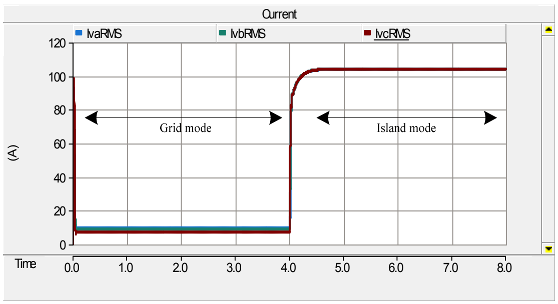

Figure 11: Output current of DG.

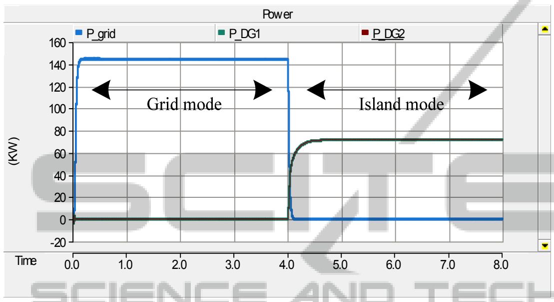

Figure 12: Active power of the DGs and network.

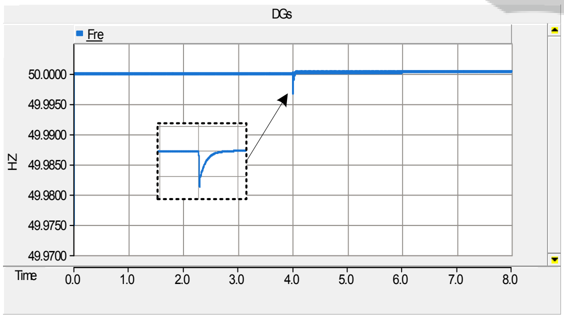

Figure 13: The frequency of DGs.

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