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# Recycling Hierarchical Control Strategy of Conventional Grids for Decentralized Power Supply Systems

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## 1. Introduction

The objective is to develop an efficient control strategy, which is adaptable and flexible for power electronic inverter based Distributed Generation (DG) to interconnect to each other and to existing power systems. Since the proposed control strategy will be developed based on the hierarchical control structure of conventional power systems in [1, 2], it is able to handle not only modern DG sources, but also conventional sources. The general overview of the hierarchical control levels through inverter based DG are structured as shown in Fig. 1. These hierarchical control levels are the primary control at unit level, the secondary control at local level and the tertiary control at supervisory level. Moreover, as mentioned, the active controlled region of the grid is covered by higher voltage levels. With the proposed strategy, this controlled region can be expanded to medium voltage and low voltage distribution networks by active grid integration of Distributed Energy Resource (DER) based Energy Conversion Systems (ECSs) through inverters. The future inverters must be operating as intelligent and multi-functional interfaces between any ECS and grid in [3, 4].

## 2. Control strategy of distributed generation based on conventional power systems

Future power distribution requires extra expandability and flexibility in the integration of DG. The inverter which is used for interfacing DERs to the grids is an important part of a DG system. Therefore, the control strategy in the interconnected grids should be combined with the control methodology of inverters (grid forming, grid supporting and grid parallel modes). Load management, synchronization and load sharing with respect to generation rating, meteorological forecasting and user settings, is required in order to implement a control methodology of inverters into an interconnected system. Moreover, due to the flexibility and expandability of an inverters' control strategy, inverters in different feeding modes can be implemented into interconnected grids. In the following sections, the description and function of hierarchical control strategies are clarified.

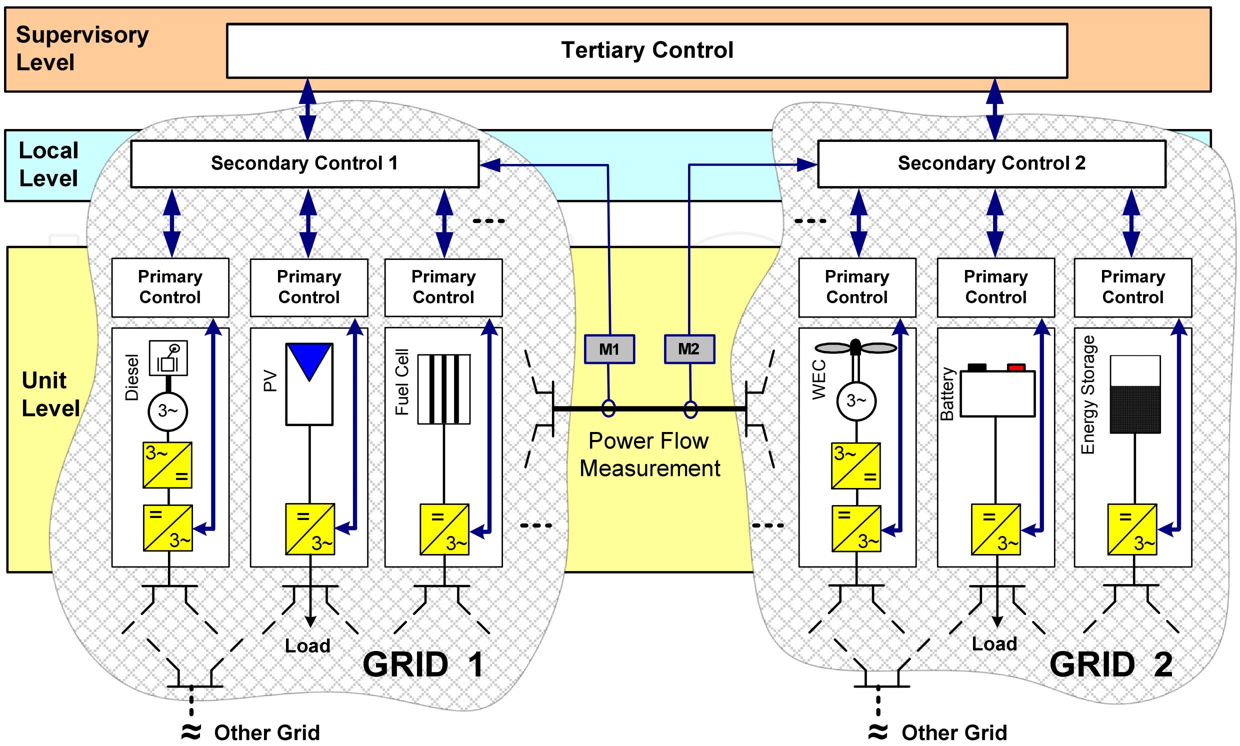



Fig. 1. Overview of hierarchy control strategy in interconnected grids.

### 2.1 Primary control

According to the future requirements of power supply systems, DER based DG should be actively integrated into the grid control. The power electronics like inverters are the primary interfaces that could fulfill this purpose. This inverter is needed to match the requirements of decentralized electric power systems [12], which must be enabled to be actively integrated into the control of the power system's state variables (frequency and voltage). Normally, the power produced by ECSs is DC power. This is fed to the grid through the inverter that produces an AC output of a specific voltage magnitude and frequency. This means that inverters provide decoupling between the voltages across the terminals of the ECSs from one side and the grid voltage from the other side. It also provides a decoupling between the frequency of the ECSs from one side and the grid frequency from the other side. The philosophy of inverter topologies is categorized as shown in Fig. 2. The inverter topologies are based on power flow from an ECS into a grid, which may be driven by a grid or by ECS itself.

Feeding modes of the inverter can be separated into two types, which are ECS driven feeding and grid driven feeding. A grid can be designed via several inverters with different operating functions and power ratings as discussed in [13].

An ECS driven feeding mode may be realized through a grid parallel inverter. In a grid driven feeding mode, the power flow from the ECS is controlled regarding the power requirements of the grid while in an ECS driven feeding mode, the power flow is controlled according to the requirement of the ECS itself. A grid feeding mode can be realized through two different cases, which are grid forming and grid supporting modes. Moreover, coupling mode such as droop control is defined also as a control function in primary control, which is needed for power sharing purpose when inverters are operated in parallel. The basic control function of primary control for inverters is summarized as shown in Table 1. In the following part of this chapter, only the structure of grid feeding mode is clarified, since it provides the active grid integration control function.

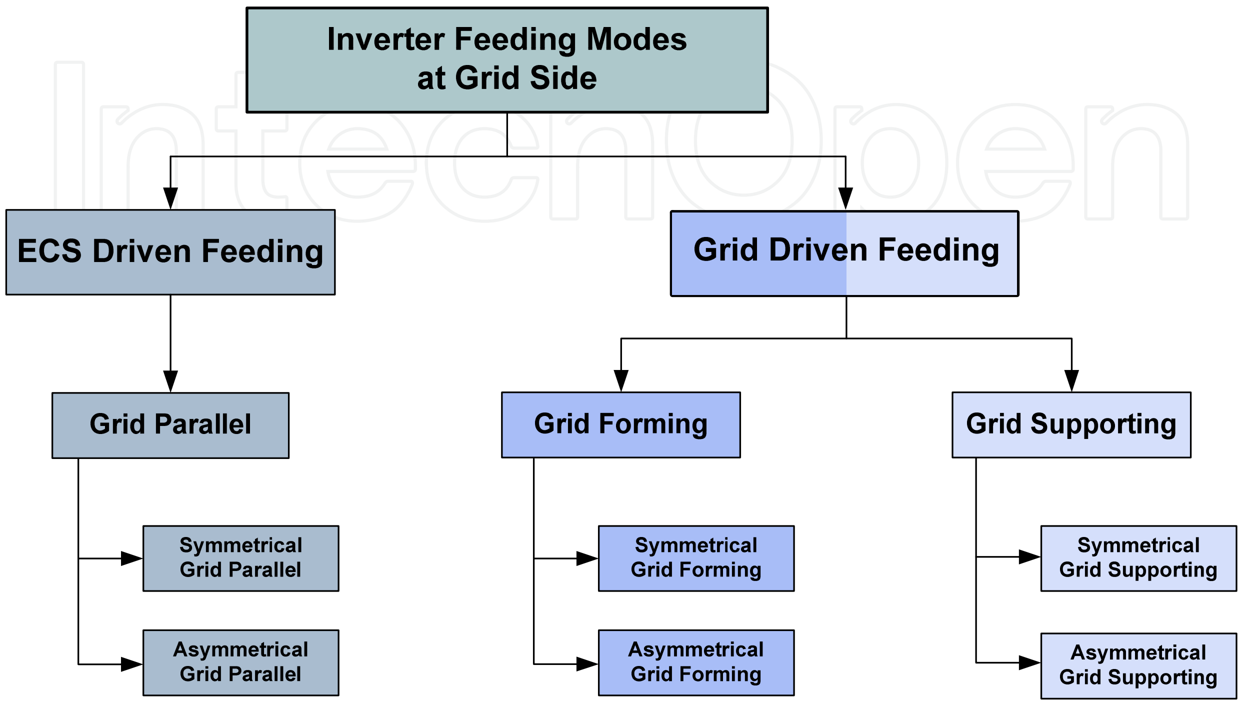



Fig. 2. Feeding modes related to the grid side [13].

| Mode | Functionalities |
|---|---|
| Grid Forming | *f*- and *V*-control with nominal reference values (grid side driven) |
| Grid Supporting | *P*- and *Q*-control with external reference values from load dispatcher (grid side driven) |
| Grid Supporting | *P*- and *V*-control with external reference values from load dispatcher (grid side driven) |
| Coupling | $\Delta f/\Delta P$ and $\Delta V/\Delta Q$ droop (grid side driven)<br>$\Delta P/\Delta f$ and $\Delta Q/\Delta V$ droop (grid side driven) |
| Grid Parallel | *P*- (and *Q*-) control with reference values from source (unit side driven) |

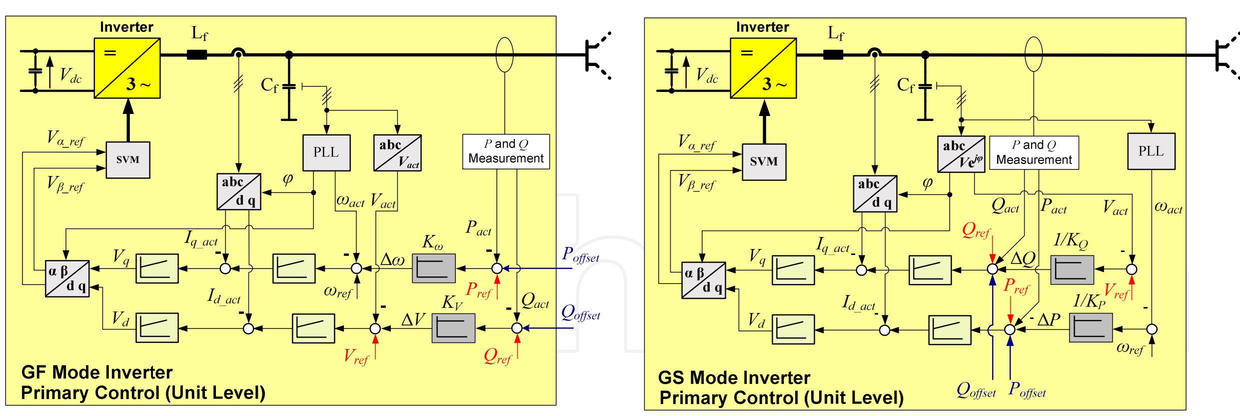
Table 1. Basic control functions of primary control.

### 2.1.1 Primary control of grid forming mode inverter

A grid forming mode inverter is responsible for establishing and maintaining the state variables (voltage and frequency) of the grid. This is done by adjusting its power production to keep the power balance in the system. It also has to feed as much current into the grid as necessary. In the control scheme of the grid forming mode inverter, the voltage is controlled by the d-component, while the frequency is controlled by the q-component. The power injection in the connection point of the inverter is related to active and reactive power controllers. In addition, as inverters are parallel operated, synchronization and load sharing are also required in the control systems. A grid forming mode inverter includes conventional droop control functions at the primary control in the unit level as shown in Fig. 3.a. The load sharing is handled, using the $\Delta\omega/\Delta P$ and $\Delta V/\Delta Q$ conventional droop control functions. The voltage droop ($\Delta V/\Delta Q$) is related to the reactive power variation of the grid and the frequency droop ($\Delta\omega/\Delta P$) is related to the active power. Moreover, at the summation points of the active and reactive power controls, the offset power of the active power and reactive power are fed from the secondary control. Further information of the grid forming mode inverter included control structure is discussed in detail in [4], [6-13]. Therefore, the svm, dq transformation and PLL blocks will be not described.

### 2.1.2 Primary control of grid supporting mode inverter

A grid supporting mode inverter produces a predefined amount of power (active and/or reactive powers), which is normally specified by a management control unit. These predefined amounts of power can be adjusted according to the system requirements and user settings via the higher control level (e.g. secondary and tertiary controls). A grid-supporting unit acquires its frequency from the grid as there is only one frequency in the grid. Therefore, if the grid frequency changes due to any disturbance, the frequency of the grid supporting mode inverter follows that change. The control strategy for the grid supporting mode inverter included conventional droop control functions at the primary control in the unit level is shown in Fig. 3.b. The grid supporting mode inverter generally consists of four controllers, two for the current (*id* and *iq*), and two for the power (*P* and *Q*). Active power (*P*) is controlled by the real part of the grid current "*id*", while reactive power (*Q*) is controlled by the imaginary part "*iq*". The offset power from the secondary control is fed into the summation points of the active and reactive power controls. Further information of the grid supporting mode inverter including control structure is discussed in [4].




(a) (b)

Fig. 3. (a) Grid forming mode inverter with traditional droop controls [4]; (b) Grid forming mode inverter with traditional droop controls [4].

### 2.2 Secondary control

The secondary control is a centralized automatic function to regulate the generation in a control area based on secondary control reserve in order to balance power within that certain control area or control block and maintain interchange power flow, as well as the stabilization of the system frequency within the control area. In future power systems, the secondary control is also needed for local control in specific areas. This is possible leading to the cluster strategy using the secondary control, which is proposed and discussed in detail in [5]. As mentioned, the control functions of the interconnected DG power system are adapted from the conventional system. All the basic control functions of secondary control at the local level also follow from the control strategy of conventional system as follows:

- Maintain and control the state variables voltages and frequency to the nominal rated values
- Control the power exchange of interconnected grids
- Detect and maintain local power unbalances such as tie lines and interconnection points

In general, the secondary control has two main controls. The first one is the control that is responsible for frequency and active power. The second one is responsible for voltage and reactive power. Both controls are explained in detail as follows:

### 2.2.1 Frequency and active power control

The secondary control of DG power systems implemented through inverters is adapted from the secondary control of conventional power systems. The secondary control functionalities of DG power systems are similar to the conventional one, which is responsible for maintaining frequency, balancing power in the grid and transferring power between the grids. Therefore, the technical principles and fundamental backgrounds are not again described in detail. However, there are important issues of secondary control related to frequency and active power control in DG that should be taken into consideration. The operation control of secondary control should temporarily disconnect any certain responsible area from the main grids whenever a risk occurs such as unintentional islanding, grid instability, etc. In this section, the control structure of frequency and active power control is focused on. Fig. 4. shows the frequency and active power control for interconnected grids. The system frequency fact needs to be fed to the droop control. The system frequency ($f_{act}$) needs to be fed to the droop control. The droop factor is equal to the droop factors summation of the inverters in the grid. In addition, the active power flows are measured at the connection points of the grids. Both power signals are fed to the summation point with the active power transfer reference, which is managed from tertiary control at supervisory level. Later on, the summed signal will go through the PI controller and be sent to each primary control at unit level with the sharing factors for each one.

### 2.2.2 Voltage and reactive power control

As mentioned, the new control strategy should be adapted based on conventional power systems. Therefore, in case of the voltage and reactive power control, the secondary control of the DG power system is also implemented through the inverter, which is adapted from the secondary control of conventional power systems. The load flow optimization is required to control voltage and reactive power, as the voltages in power system are more sensitive than frequency. The control structure of voltage and reactive power control in interconnected grids is shown in Fig. 5. In the interconnected point, reactive power at the bus between the grids is measured. These measured values ($Q_{12}$ and $Q_{21}$) will be adjusted to the amount of the reactive power transfer between the grid ($Q_{ref,12}$ and $Q_{ref,21}$), which are

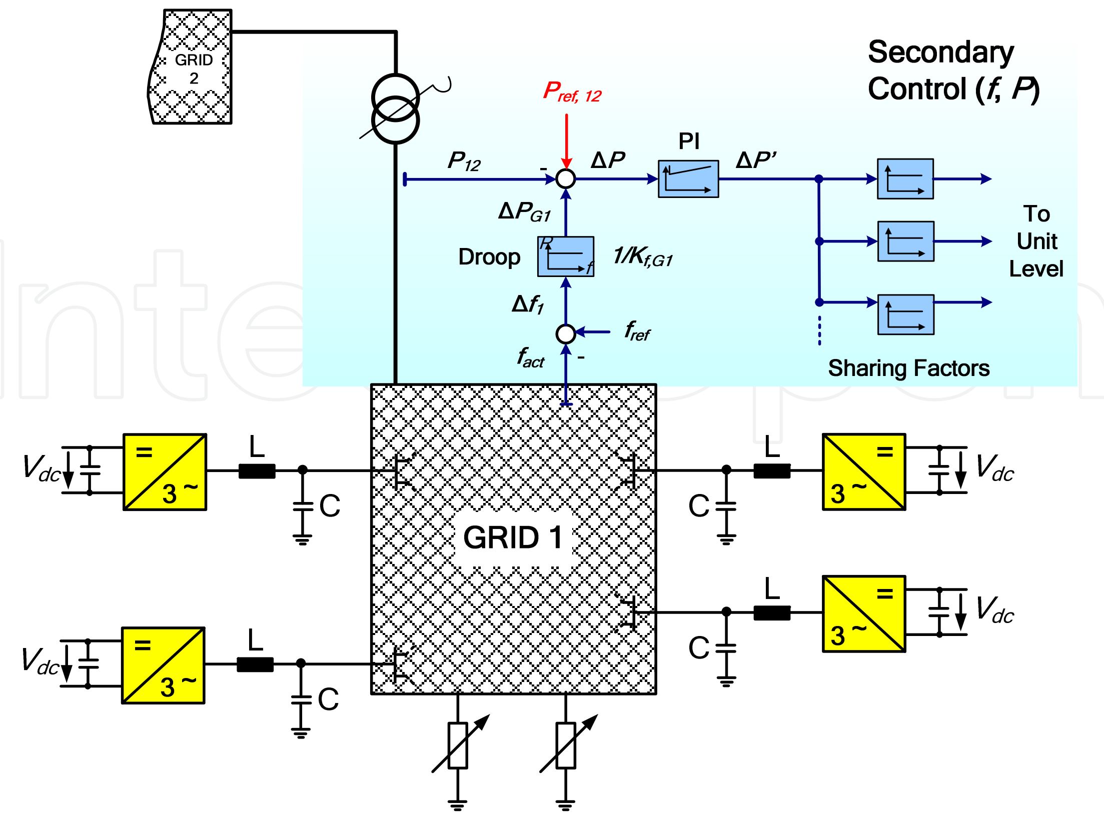



Fig. 4. Frequency and active power control with sharing factor in interconnected grids.

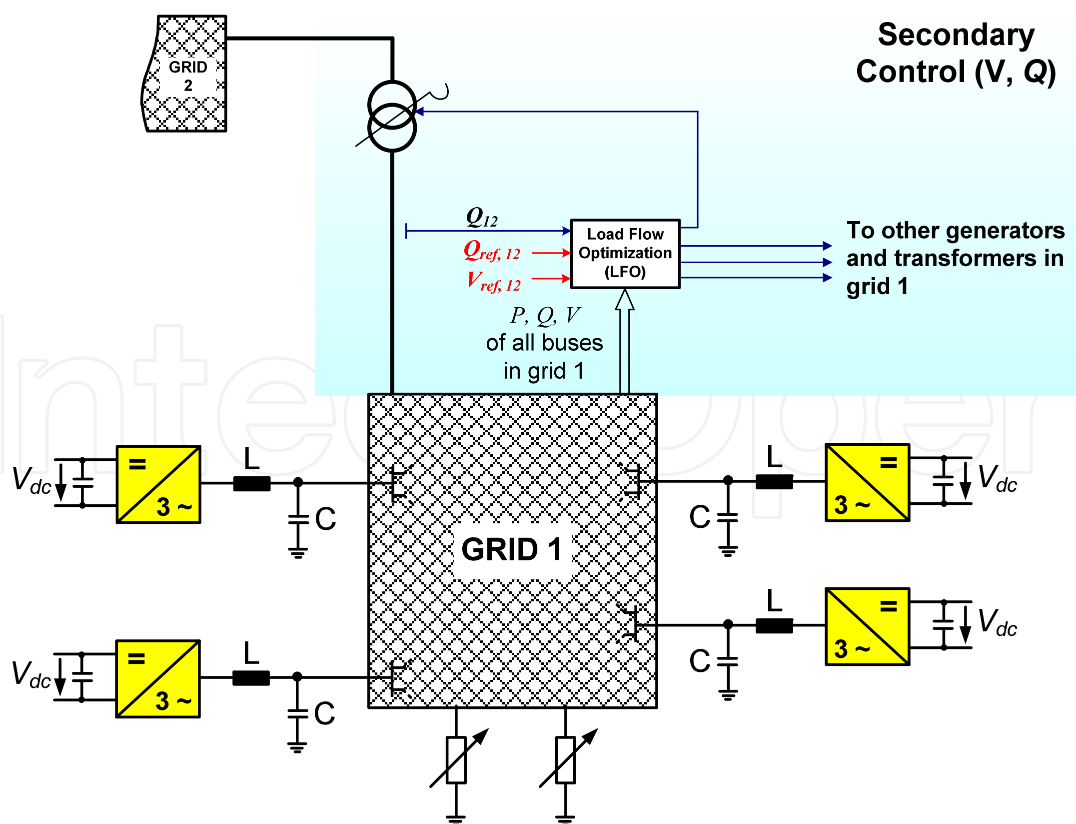



Fig. 5. Voltage and reactive power control with sharing factor for interconnected grids.

calculated from the higher control level such as the tertiary control at supervisory level (red arrows). The reactive power bus ($Q_{12}$), reference value of reactive power transfer ($Q_{ref,12}$) and reference voltage of interconnection point ($V_{ref,12}$) will be fed into the load flow optimization (LFO) block [15]. All data of bus voltage, active and reactive power in the grid are required for the calculation process of optimization. After the optimization, new offset of voltage and reactive power will be fed into primary controls as well as transformers in the grid.

## 3. Control strategy of interconnected distributed power systems

The hierarchical control strategy of the interconnected distributed power systems can be adapted based on the control structure of the conventional power systems. There are also generally three main control levels to manage the entire power system which are unit level, local level and supervisory level. This section introduces an example control structure of interconnected grids including the combination of grid forming and grid supporting inverters as shown in Fig. 6. This sample layout of control strategy in interconnected grids is controlled by the control strategy adapted from the conventional power system. The control strategy focuses directly on the flexibility of the inverter control structure that can be implemented along with the control strategy for grid interconnection.

Having a look at a grid forming mode inverter, its role is to establish and maintain the state variables (voltages and grid frequency). Therefore, in the control scheme of the grid forming mode inverter, the voltage is controlled by the d-component. In contrast, the frequency is controlled by the q-component. The power injection in the connection point of the inverter is related to active and reactive power controllers. Synchronization and load sharing are also required in the control systems. The load sharing will be handled using the voltage and frequency droop control functions for the primary control at unit level. The voltage droop is related to the reactive power variation of the grid and the frequency is related to active power. The secondary control at local level is included to bring system frequency back to nominal value, as well exchanged active and reactive power can be transferred between the grids. In addition, voltage and reactive power control can be possibly done by load flow optimization, which is adapted from conventional one in [9]. For optimization purpose, tertiary control will calculate and manage the reference values in the controllers. Note that, the optimization for voltage and reactive power is not a main focus in this work. For, the grid supporting mode inverter, it is used for power balancing and produces predefined amounts of power. These predefined amounts of power can be adjusted according to the system requirements and user settings via the secondary and tertiary controls. The grid supporting mode inverter feeds the grid with a specified amount of power, which is active and reactive power, or a combination of both. The control strategy for the grid supporting mode inverter using active and reactive power consists of four controllers, two for current ($i_d$ and $i_q$), and two for active and reactive power ($P$ and $Q$). Active power is controlled by the real part of the grid current "$i_d$", while reactive power is controlled by the imaginary part "$i_q$". For the grid parallel mode inverter, there is no need to have a secondary control, since it is a power production unit that is not controlled according to the requirements of the electrical system. However, it can be possible to implement the active and reactive power control into the grid parallel mode inverter.

This tertiary control is related to the supervisory level, which organizes energy management of the overall power system (i.e. system optimization, dispatch control strategy, load flow

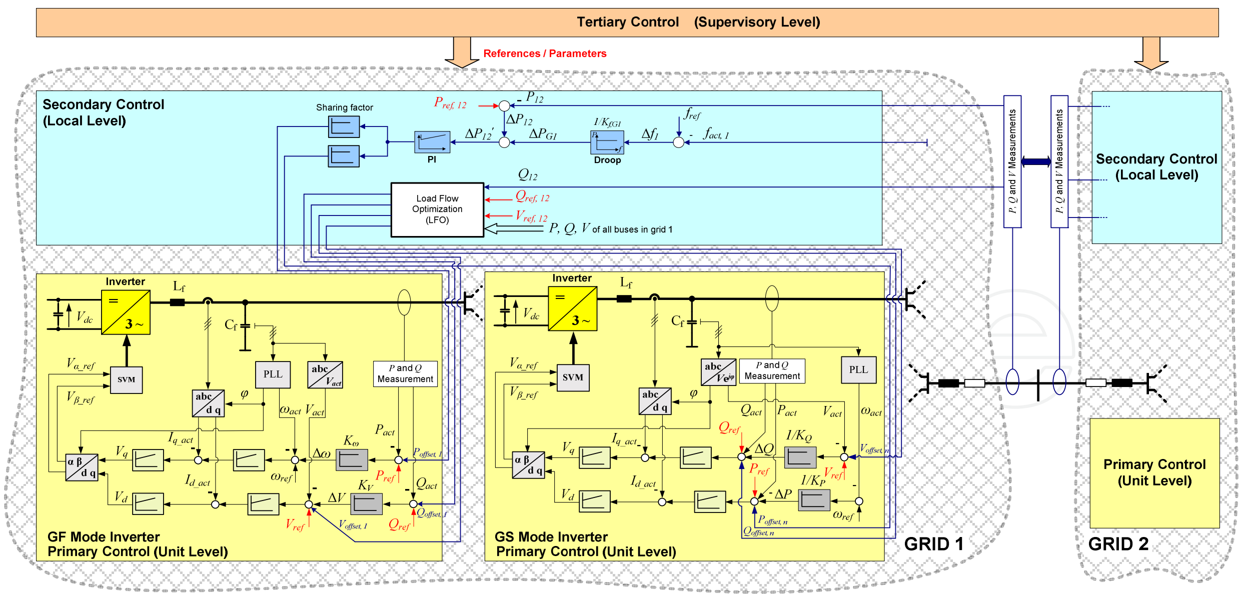



Fig. 6. Example of the control strategy in interconnected grids including grid forming and grid supporting mode inverters [6].

management, meteorological forecasting, network management and communication management). The tertiary control collects information of the interconnected grids such as forecasting data, power profile, load data, etc. The optimization is processed in this level to get the reference values fed to the local and unit levels. This also includes the optimized power dispatch between grids. However, the optimization process can be computed in other additional level depending on strategies of the control structure.

## 4. Case study

To verify the proposed control strategy, the model is tested by simulation of two grids including grid forming mode inverters as shown in Fig. 7. The first grid is supplied by grid forming mode inverters (GF1 and GF2). The Second grid is supplied by two grid forming mode inverters (GF3 and GF4). The power system operates at the rated frequency $f_{rated}$ = 50 Hz and the reference voltage line to line $V_{L\text{-}L}$ = 400 $V_{rms}$. Rated apparent power of the grid forming mode inverters is $S_r$ = 125 kVA. Both grids are linked via a tie line (NAYY 4×50 SE: R = 0.772 Ω/km and X = 0.083 Ω/km). The secondary control is included in the simulation to control power in each grid as well as power exchange between the grids. The active power and reactive power loads of the first grid are the same as those of the second grid which starts at 16 kW and 7.3 kvar. The total active power and reactive power are 32 kW and 14.6 kvar respectively. At t = 15 s, in the first grid, the active power steps up to 20.2 kW and reactive power load steps up to 7.37 kvar. Therefore, the total active and reactive powers after the load step are 36.2 kW and 14.67 kvar respectively. At t = 40 s, the exchanged active and reactive powers of 2 kW and 1 kvar respectively are transferred from the first grid to the second grid.

Active power of the inverters is shown in Figs. 8.a. At the beginning, the inverters supply active power of approximately 32 kW; around 8 kW is supplied by each grid forming mode inverters. At t = 15 s, the step load of 4.2 kW is added to the first grid. All the inverters of the system directly supply to compensate the additional load step. After the step, the secondary

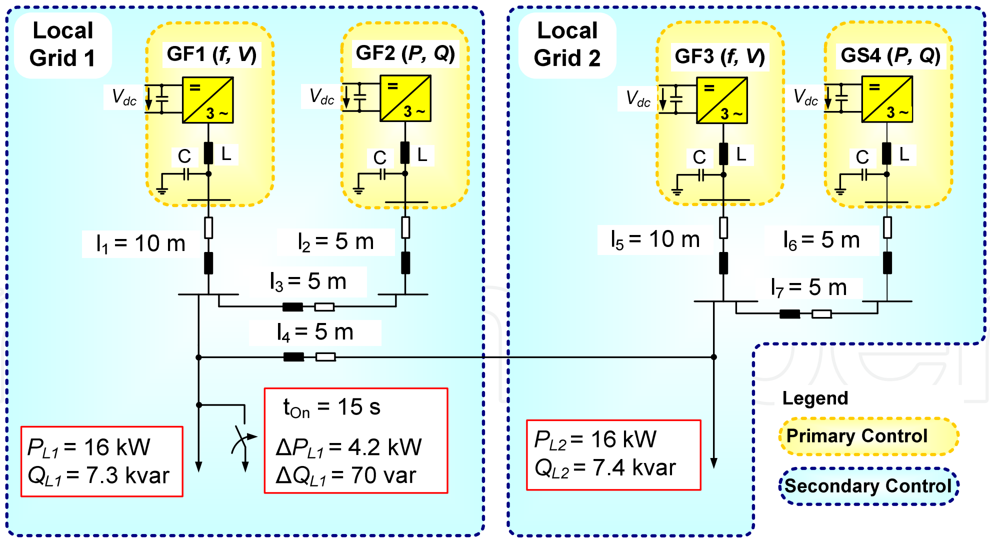



Fig. 7. Two grids including two grid forming mode inverters each.

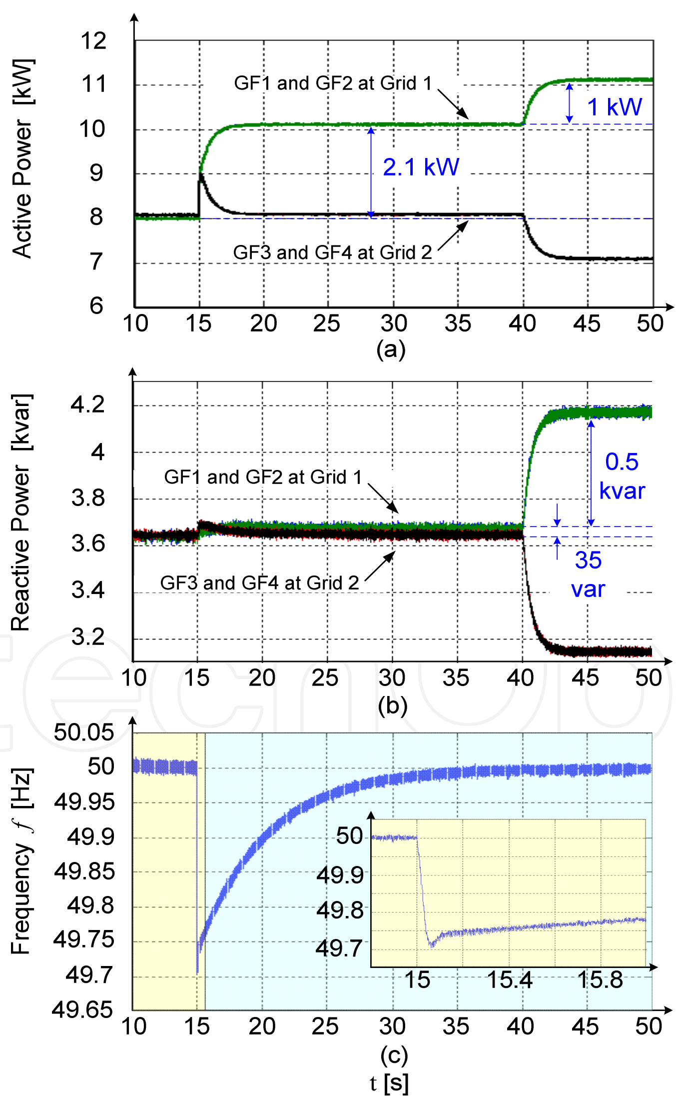



Fig. 8. (a) Active power, (b) Reactive power, (c) Frequency

control manages the generating units at the first grid to response to the disturbance to the grid by itself. Therefore, the active power of GF1 and GF2, which are located close to the first grid, are steadily increased, while active power of inverters at the second grid are steadily decreased. At t = 40 s, active power is transferred from the first grid to the second grid of 2 kW.

Reactive power of the grid forming mode inverters is shown in Fig. 8.b. At the beginning, all inverters supply reactive power of approximately 14.6 kvar. At t = 15 s, the step load of 70 var is added to the first grid. All the inverters of the system directly supply to compensate the additional load step. Later on, the inverters in the first grid will maintain themselves due to the secondary control which provides the same behavior response as the active power. At t = 40 s, the reactive power is transferred from the first grid to the second grid is 1 kvar.

System frequency is shown in Fig. 8.c. The primary and secondary controls have direct impact on the frequency behavior. Due to the droop control function of the primary control, at the load step t = 15 s, the frequency drops from the nominal frequency. This frequency drop can be brought back to the nominal value by secondary control.

## 5. Conclusion

As the penetration of DG systems in the grid is increasing, the challenge of combining large numbers of DERs in the power systems has to be carefully clarified and managed. The control strategy and management concept of the interconnected systems should be flexible and reliable to handle the various types of DG. The chapter introduces a control strategy for DG interconnected grids based on the control strategy of conventional power systems. The proposed strategy is integrating DERs and managing interconnected grids to operate in parallel. The power dispatch, exchanged power, frequency control and voltage control can be automatically managed by the proposed strategy. The simulation results illustrate that the strategy can be implemented into the power systems. The grid integration is additionally supported by adaptability, flexibility and efficiency of the proposed strategy. Mini-grids can be widely interconnected to each other and existing conventional systems to form huge power systems. Moreover, this proposed strategy is compatible with the concept of multi-level clustering power systems. The multi-level clustered secondary control strategy is the consequent development to be followed in the stepwise evolution from the historical centralized power system towards a more decentralized structure. It allows stepwise implementation and improvement of the power system control. The success of the proposed control philosophy will finally clear the way for future smart gird applications by creating a basic, technical power system control approach, based on control theory and the physical behavior of the power system. This is the fundamental basis for all other optimization, management and economic functions of the "smart grid" vision.

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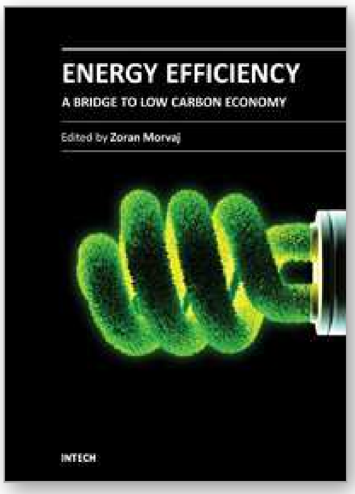


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Energy efficiency is finally a common sense term. Nowadays almost everyone knows that using energy more efficiently saves money, reduces the emissions of greenhouse gasses and lowers dependence on imported fossil fuels. We are living in a fossil age at the peak of its strength. Competition for securing resources for fuelling economic development is increasing, price of fuels will increase while availability of would gradually decline. Small nations will be first to suffer if caught unprepared in the midst of the struggle for resources among the large players. Here it is where energy efficiency has a potential to lead toward the natural next step - transition away from imported fossil fuels! Someone said that the only thing more harmful then fossil fuel is fossilized thinking. It is our sincere hope that some of chapters in this book will influence you to take a fresh look at the transition to low carbon economy and the role that energy efficiency can play in that process.