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SMART RUE smartgrids Research Unit ECE NTUA

Microgrids Concepts and Control

Nikos Hatziargyriou
Athanasios Vasilakis

Smart Grids Research Unit - Smart RUE
School of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece

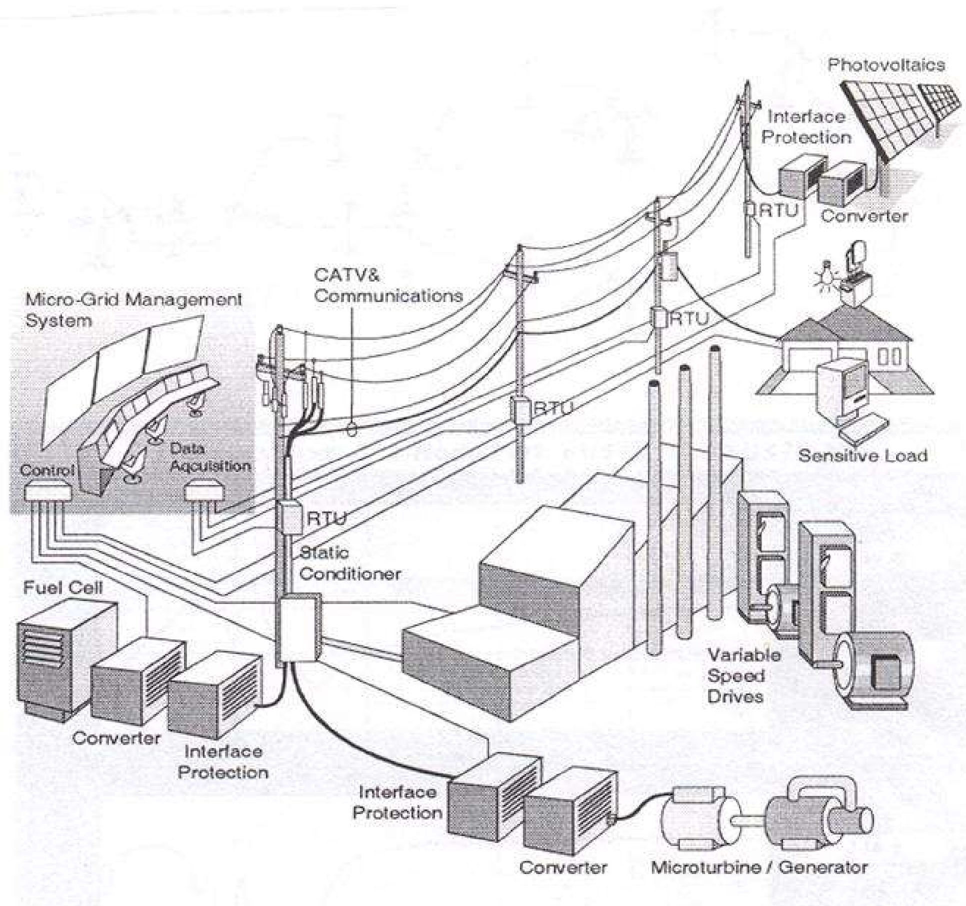
Smart/Micro Grids Research Center, Iranian Society of Smart Grid,
IEEE Iran Section, October 20, 2020

Microgrids: The Building Blocks of SmartGrids

http://www.microgrids.eu

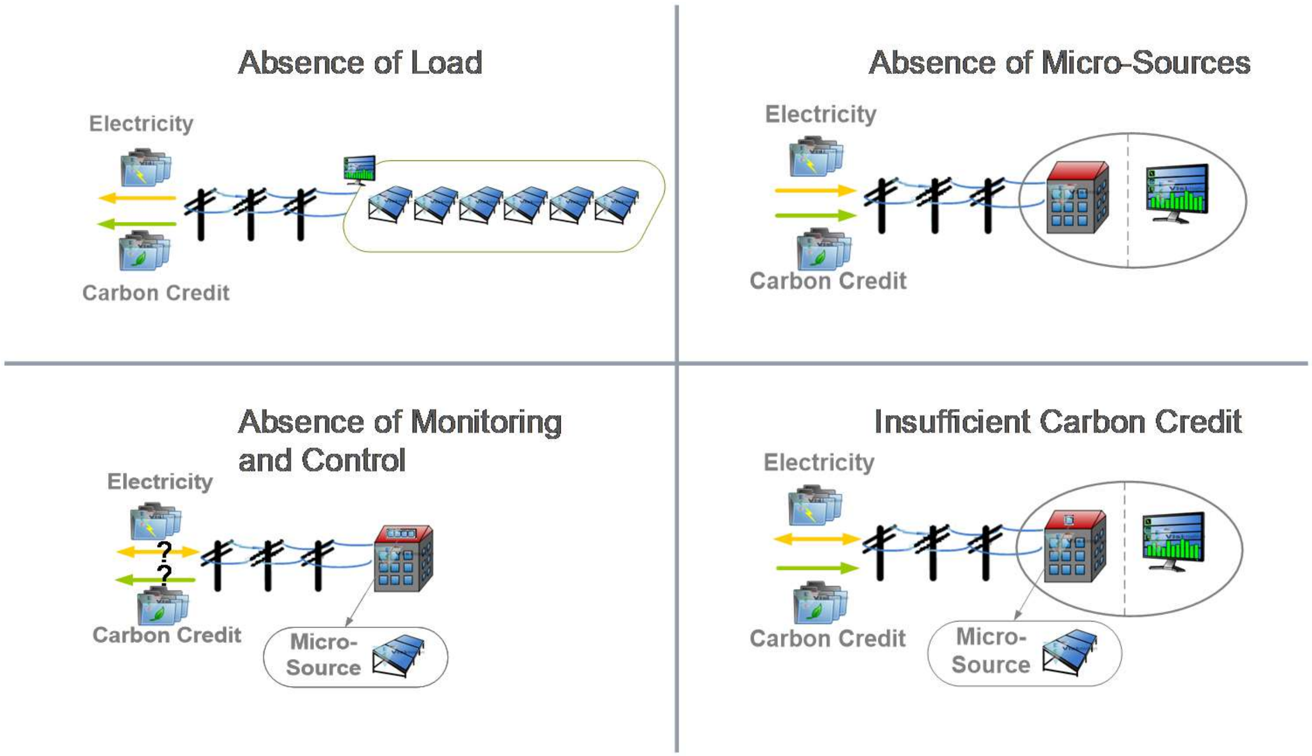
Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way, either while connected to the main power network and/or while islanded.

(CIGRE WG C6.22)



EU Microgrids (ENK5-CT-2002-00610) and MOREMICROGRIDS (PL019864)

What are not Microgrids



Three essential Microgrid features: local load, local micro-sources, and intelligent control.
Different than DG interconnection or Demand Side Integration.

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Microgrids vs. Virtual Power Plants

A **virtual power plant** (VPP) is a cluster of DER which is collectively operated by a central control entity. A VPP can replace a conventional power plant, while providing higher efficiency and more flexibility.

Distinct differences:

- Locality
- Size
- Consumer Focus

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Microgrids vs. Local Energy Communities

EC Electricity Directive COM(2016) 864 final/2

An association, a cooperative, a partnership, a non-profit organisation or other legal entity which is effectively controlled by local shareholders or members, generally value- rather than profit-driven, involved in distributed generation and in performing activities of a distribution system operator, supplier or aggregator at local level, including across borders

Local Energy Communities are based on Microgrids structures

Microgrids ≠ Local Energy Communities

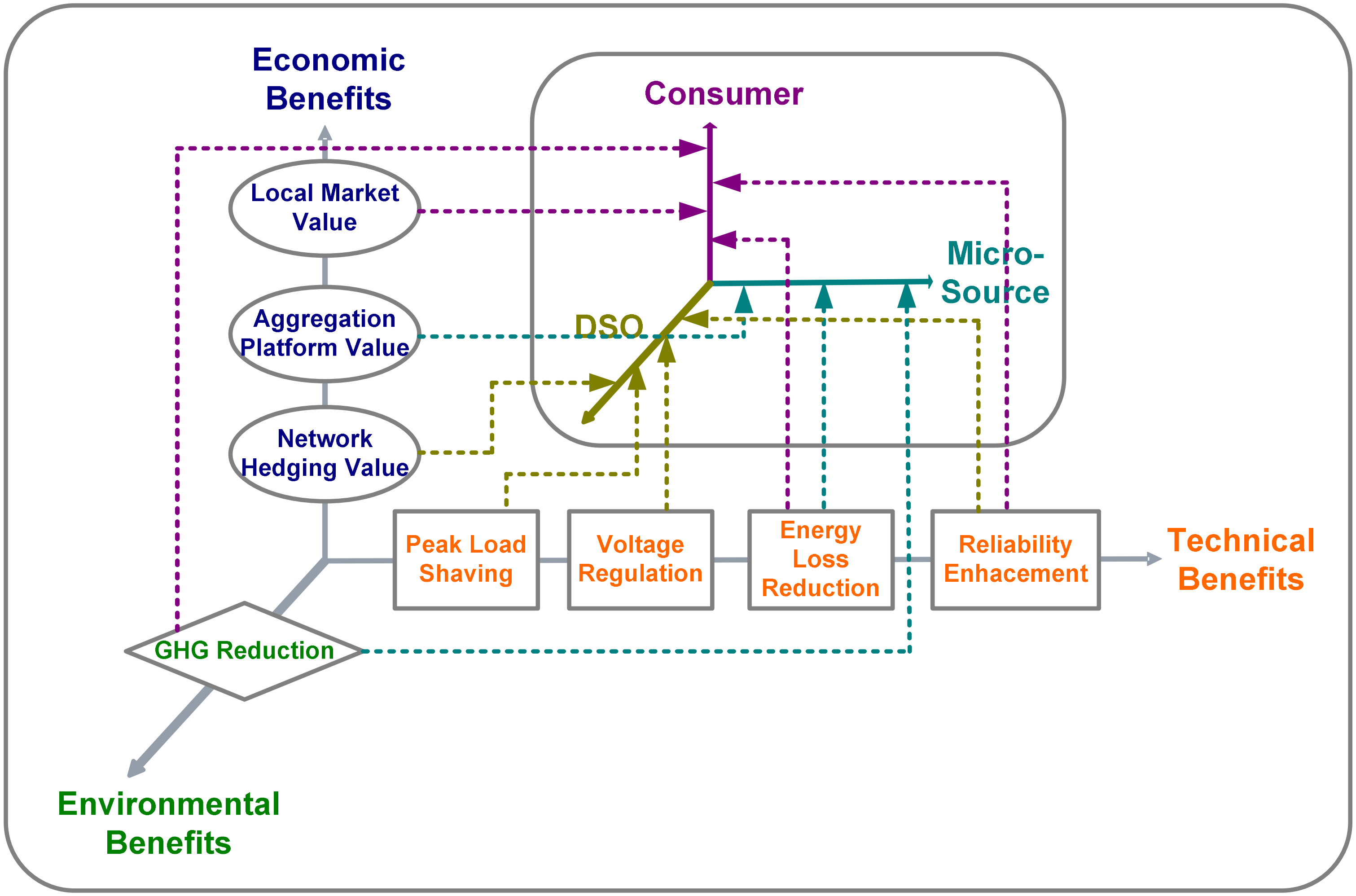
Long Tradition in Europe: in **Germany** over 650 Stadtwerke (local utility companies that provide heat and electricity) ,
in the **Netherlands**, over 200 local initiatives involved in RE, including over 55 registered cooperatives,
in **Denmark** 100s of electricity production (CHP) and community district heating (CDH) systems, 100 wind cooperatives.

DER Technical, economic and environmental benefits

- Energy efficiency
- Minimisation of the overall energy consumption
- Improved environmental impact
- Improvement of energy system reliability and resilience
- Network benefits
- Cost efficient electricity infrastructure replacement strategies

Microgrids as the efficient DER integration structures are able to unlock the full benefits of DER

Benefits by Criteria & Stakeholders



"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Technical Challenges

- Small size (challenging management)
- Use of different generation technologies (prime movers)
- Presence of power electronic interfaces
- Relatively large imbalances between load and generation to be managed (significant load participation required, need for new technologies, review of the boundaries of microgrids)
- Specific network characteristics (strong interaction between active and reactive power, control and market implications)
- Protection and Safety / static switch
- Communication requirements
- Complex relations among multiple subsystems implies hierarchical multi-layer approaches for their control.

Multi-Layer Hierarchical Structures

Common properties of Hierachical Systems :

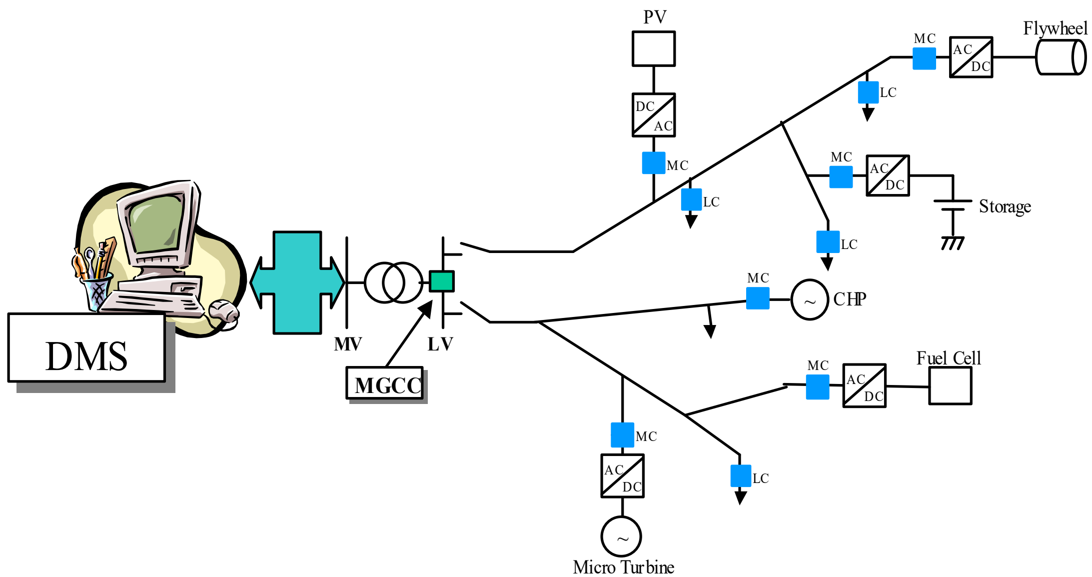
i) vertical arrangement of subsystems,
ii) priority of action of the higher level subsystems and
iii) dependence of the higher level subsystems upon actual performance of the lower levels.

Decoupling enables more efficient and detailed study of systems behavior and simplifies mathematical formalization.

Decision problems at higher levels are normally more complex, since they need to take into consideration the slower aspects of the overall systems behavior. The concept of layers is referred to the vertical decomposition of a decision problem into sub-problems.

Microgrids Controllers

MicroGrid Central Controller (MGCC) promotes technical and economical operation, interface with loads and micro sources and DMS; provides set points or supervises LC and MC; MC and LC Controllers: interfaces to control interruptible loads and DGs



Centralized vs. Decentralized Control

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Microgrids Hierarchical Control Levels

Primary control

Primary control operates at the fastest timescale. It maintains voltage and frequency stability and ensures proper sharing among the generators. Technical realization is usually ensured by decentralized loop controllers providing several advantages in terms of plug and play capabilities.

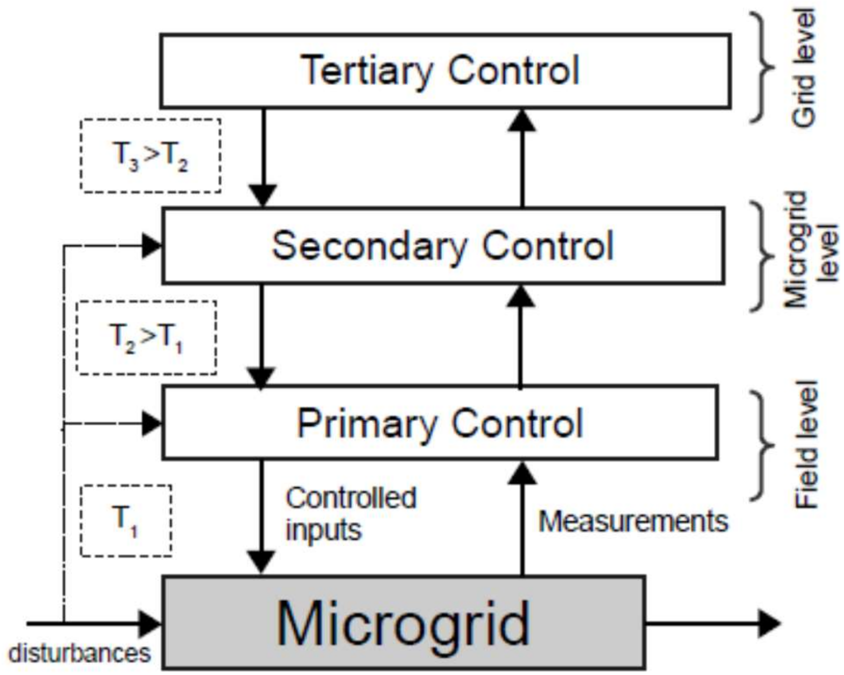
Secondary control

Secondary control is responsible for the mitigation of voltage and frequency deviations introduced by primary control. It can also facilitate the synchronization with the upstream network and perform optimal economic management. This control layer acts on a slower time scale and its computed control outputs are provided to the primary control level.

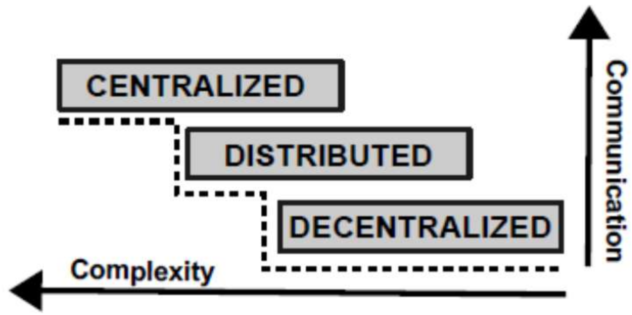
Tertiary control

Tertiary control determines the Microgrids' interactions with the upstream network and with the neighboring MGs being part of the overall distribution system efficient and optimal operation

Microgrids Control Levels Interactions



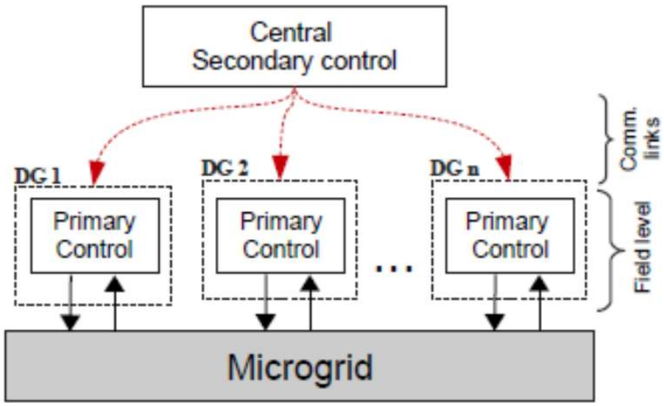
Control Structures



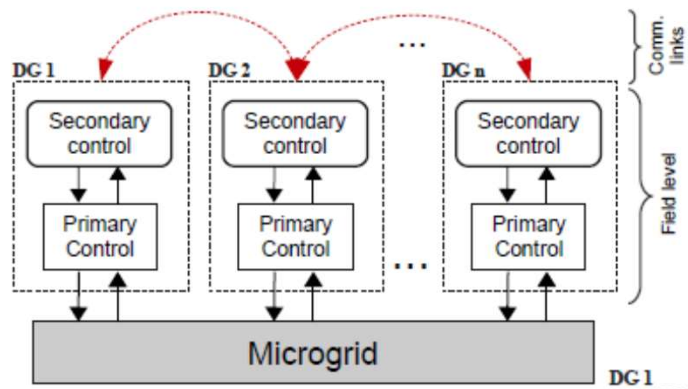
Differences in the complexity of the model and the necessary communication among controllers of different operating layers of the control system hierarchy.

Decentralized: control system composed of individual controllers, which do not share any information, independently of whether or not the selection of the controlled variables takes into account the interactions within the system.
Distributed*:* some information is shared among controllers, so that each has some knowledge about the behavior of the others, thus raising the overall performance.
Centralized*:* a single controller manages and communicates with all other components control decisions based on knowledge of all control inputs optimized in a single optimization problem.

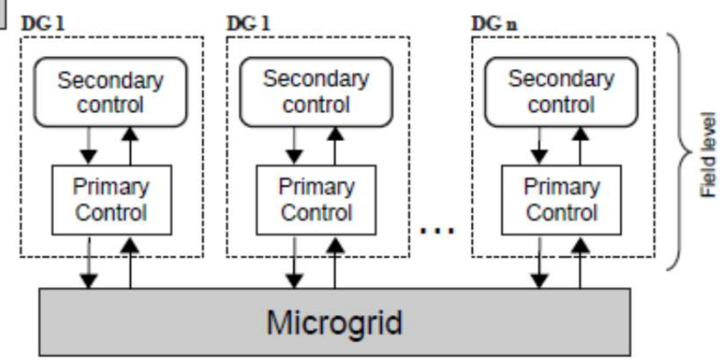
Microgrids Control Structures



Centralized Structure



Distributed Structure



Decentralized Structure

Choice of structure depends on DG ownership, scale, ‘plug and play’, etc.

Advantages and Disadvantages of Microgrids Control Structures

TABLE I

Method	Advantages	Disadvantages
Centralized	• Global optimal solutions	• Significant computational complexity • Communication infrastructure required • Stability affected by communication network • Reduced scalability
Distributed	• Better reliability • Reduced computational burden • Increased scalability	• Communication infrastructure required • Stability affected by communication network • Sub-optimal solutions
Decentralized	• Higher Reliability • No communication requirements • Reduced computational burden • Increased scalability	• No global optimal solutions

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Primary Control of Microgrids

- Maintain Stability
- Mitigate Frequency and Voltage Transients
- Proper active and reactive power sharing between the units

Classification of Primary Control

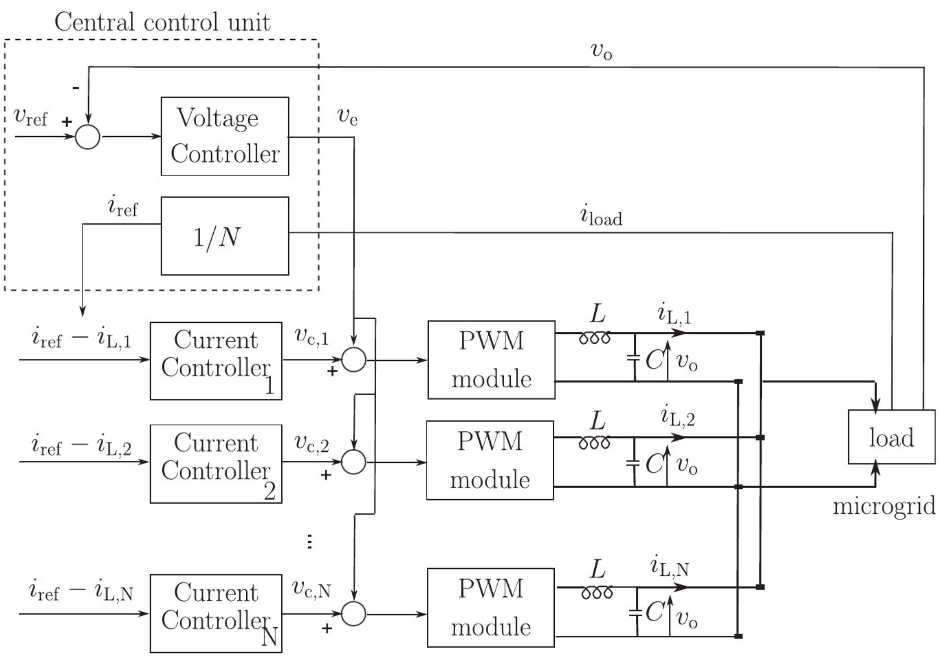
- Classification of the grid-forming control strategies can be based on the **communication requirements**.
- Communication free (decentralized) approaches are based exclusively on local measurements.

Communication Based	Communication Free (Decentralized)
➢ Concentrated control (Centralized) ➢ Master/Slave control (Centralized) ➢ Distributed/average load sharing Control (Distributed)	➢ Conventional droop control (Pf/VQ) ➢ VP/FQ droop control ➢ Virtual impedance control ➢ Frame transformation control

Primary Control – Communication Based Methods

Concentrated control (Centralized scheme)

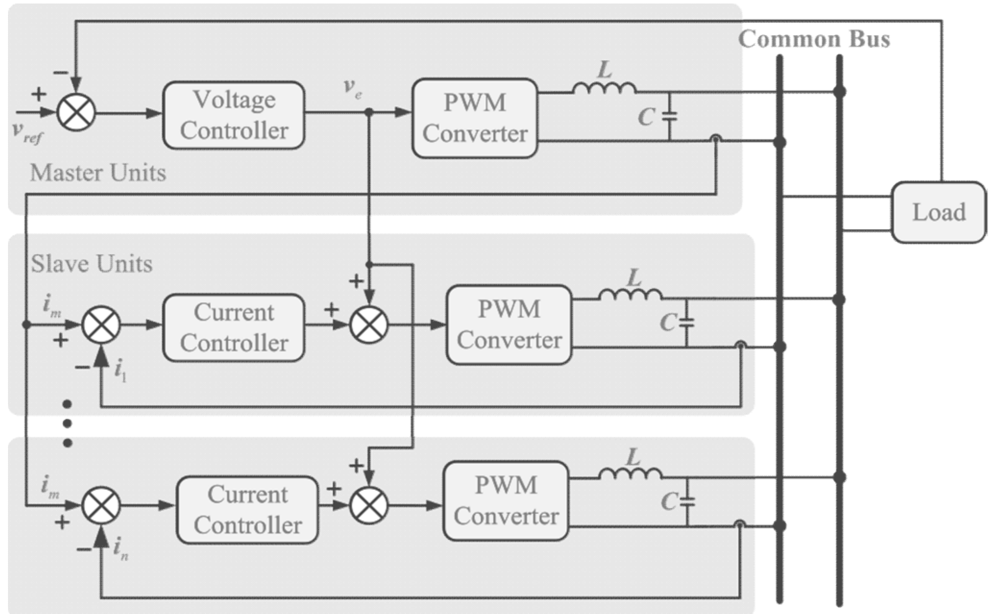
- Central controller coordinates the power-electronic interfaces in the Microgrid
- Central controller defines the set-value of the current for each module.
- Accurate power sharing is achieved in steady state as well as during transients
- A communication link between the central controller and each unit is required.
- Central control makes it difficult to expand the system
- Single point of failure (Central Control Unit)



Vandoorn et al. - 2013 - Review of primary control strategies for islanded microgrids with power-electronic interfaces

Master Slave Control (Centralized scheme)

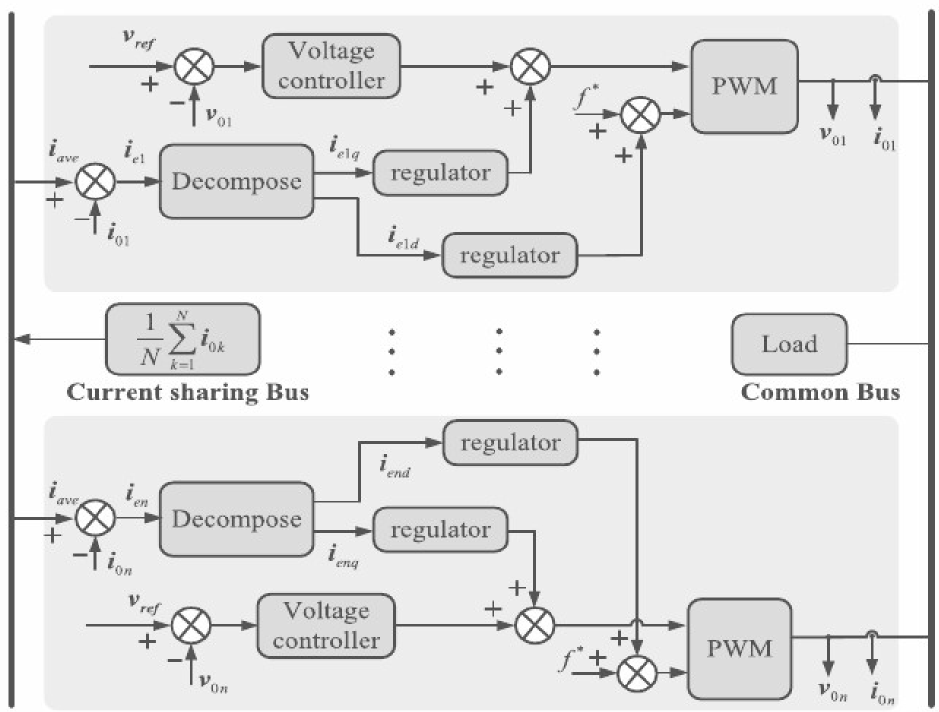
- Used for paralleling inverter units in the case of short distances (UPS)
- Master converter operates as a VSC and regulates the output voltage
- Slave converters behave as current source converters that follow the current pattern of the master converter.
- Achieve good voltage regulation and power sharing, even with non-identical modules
- System is difficult to expand
- High bandwidth communication channel
- No redundancy



Han et al. - 2016 - Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids

Distributed Control

- No central controller needed (increased reliability)
- Additional current control loop is used to enforce each converter to track the same average reference current.
- Requires a current sharing communication bus and reference synchronization for the voltage
- Voltage regulation and fundamental power sharing are well controlled
- Interconnections between the inverters are still necessary, degrades the flexibility of the system



Han et al. - 2016 - Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids

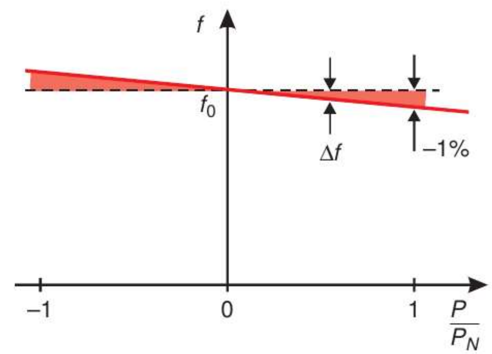
Comparison of communication based methods

Communication based control	**Advantages**	**Disadvantages**
Concentrated control	✓ Good power sharing in steady state and transients ✓ Constant voltage and frequency regulation	✗ High bandwidth communication required ✗ Low reliability and dependability
Master/slave control	✓ Recover the output voltage easily ✓ Good power sharing in steady state	✗ High current overshoot during transients ✗ High bandwidth communication required ✗ Low redundancy
Distributed control	✓ Symmetrical for every module ✓ Constant voltage and fundamental power sharing	✗ Require communication bus ✗ Degrade the flexibility of the system

Primary Control – Communication Free Methods

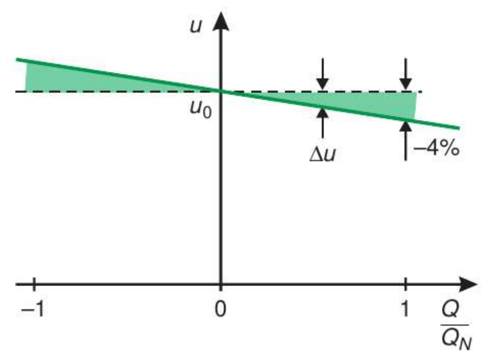
Droop Based control

- Once the Microgrid load changes, DG will carry a larger load and therefore its frequency will drop.
- In conventional primary control, power sharing is performed by active and reactive droops.
- Avoid communication dependency
- Mimic the operation of synchronous generators
- It is based on the assumption active and reactive power are mainly affected by the frequency and the voltage, respectively.
- $m_{P,}$ n_Q influence the network stability
- Droop gains selected usually according to the nominal rating of the units



$$m_P = \frac{f_i - f_{\min}}{P_i - P_{i,\max}}$$

$$n_Q = \frac{E_{i,\max} - E_{i,\min}}{Q_{i,\min} - Q_{i,\max}}$$

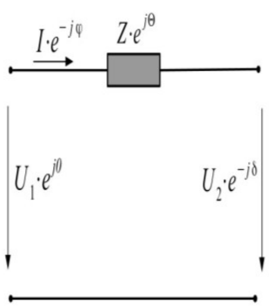


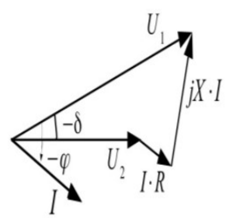
N. Hatziargyriou, Ed., Microgrids: Architectures and Control, 1st ed.
Guerrero et al.: Advanced Control Architectures For Intelligent Microgrids—Part I

Issues with conventional droop control in Microgrids

- ❖R/X ratio of lines degrade the effectiveness (the basic assumption for droop control is not true for MV & LV systems)
- ❖Inaccurate Power sharing
- ❖Issues when serve Nonlinear loads
- ❖Poor harmonic sharing
- ❖Poor transient performance

Line Type	X/R ratio	Active/Reactive Power – Voltage/Angle relations
HV	>>1	$\delta = f(P)$, $\Delta V = f(Q)$
MV	~= 1	$\delta = f(P,Q)$, $\Delta V = f(P,Q)$
LV	<<1	$\delta = f(Q)$, $\Delta V = f(P)$





$$\bar{S}=P+jQ=\bar{U}_1\cdot\bar{I}^*=\bar{U}_1\cdot\left(\frac{U_1-U_2}{Z}\right)^*=\frac{U_1^2}{Z}\cdot e^{j\theta}-\frac{U_1U_2}{Z}\cdot e^{j(\theta+\delta)} \quad \text{(Eq. 1)}$$

General case: both X and R are to be considered

$$P=\frac{U_1^2}{Z}\cdot\cos(\theta)-\frac{U_1U_2}{Z}\cdot\cos(\theta+\delta)\Big|_{Z\cdot e^{j\theta}=R+jX} \Rightarrow \quad U_2\cdot\sin\delta=\frac{XP-RQ}{U_1}$$

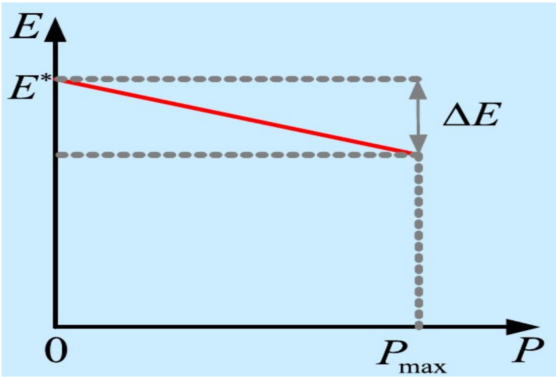
$$Q=\frac{U_1^2}{Z}\cdot\sin(\theta)-\frac{U_1U_2}{Z}\cdot\sin(\theta+\delta) \qquad U_1-U_2\cdot\cos\delta=\frac{RP+XQ}{U_1}$$

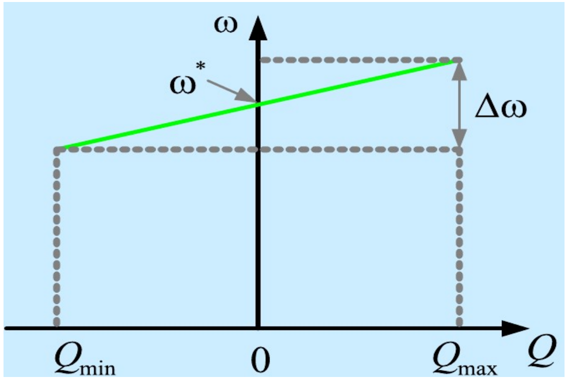
$$\boxed{\begin{matrix}\sin(\delta)\simeq\delta \\ \cos(\delta)\simeq 1\end{matrix} \Rightarrow \quad \delta\simeq\frac{XP-RQ}{U_1\cdot U_2} \qquad U_1-U_2\simeq\frac{RP+XQ}{U_1} \quad \text{(Eq. 2)}}$$

Different Droop Based Approaches– Q(f) & P(V) control for LV Microgrids

Based on the assumption that in LV networks *R » X* :

- ❖ Active power is mainly linked with the voltage difference
- ❖ Reactive power is mainly linked with the phase angle, hence frequency
- ❖ Improved performance for controlling LV microgrid
- ❖ VP/FQ method strongly depends on system parameters
- ❖ It is also unable to properly share the load active current if DG units contribute evenly with large central generators

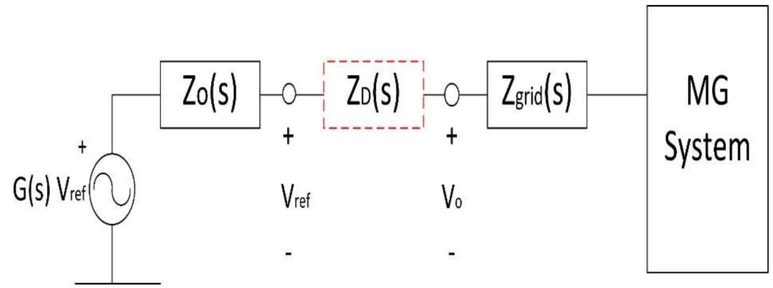


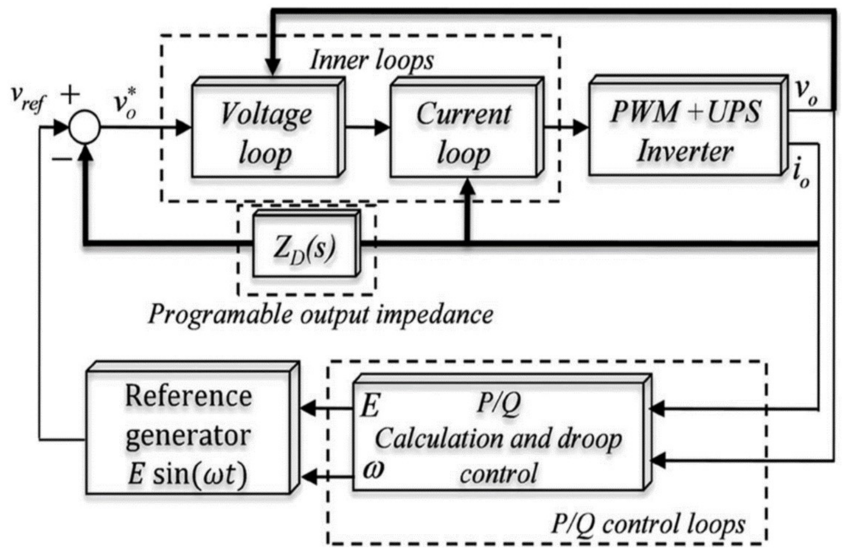


Virtual Impedance Approach

DG units through their control can modify their equivalent network impedance to modify the network dynamics:

- ❖ The virtual impedance (ZD) is included in the loop to change the resistive lines to inductive
- ❖ Inverter output impedance (Zo) is affected by its filter and control
- ❖ Z_D is designed to be bigger than Z_O
- ❖ Z_D can be chosen arbitrarily and is without actual power losses.
- ❖ Special care for current spikes when the DG is initially connected
- ❖ With proper modification harmonic current sharing can be achieved

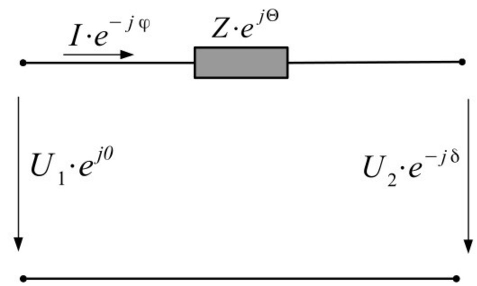


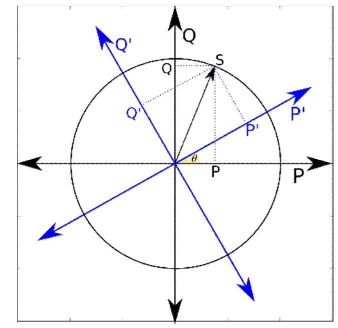


Josep M. Guerrero et al. - 2011 - Hierarchical Control of Droop-Controlled AC and DC Microgrids

Frame Transformation Method

Decouple the impact of active power to voltage and reactive power to frequency:





- In general, both line reactance X and resistance R need to be considered.
- An orthogonal linear rotational transformation matrix T from P-Q frame to the modified P'-Q' frame is used.
- An estimation of R/X is sufficient to perform the method.
- In P'-Q' frame, can effectively decouple real and reactive power flows
- Improve the system transient and stability performance

$$\theta = \tan^{-1}\frac{r}{x}$$

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = T \cdot \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{X}{Z} & \frac{-R}{Z} \\ \frac{R}{Z} & \frac{X}{Z} \end{bmatrix}\begin{bmatrix} P \\ Q \end{bmatrix}$$

$$\delta \approx \frac{\mathrm{XP}-\mathrm{RQ}}{U_1 U_2} = \frac{ZP'}{U_1 U_2} \qquad U_1 - U_2 \approx \frac{RP+\mathrm{XQ}}{U_1 U_2} = \frac{ZQ'}{U_1}$$

$$f - f_{ref} = -m_p(P' - P_o') = -m_p\frac{X}{Z}(P - P_o) - m_p\frac{R}{Z}(Q - Q_o)$$

$$U_1 - U_{1,ref} = -n_q(Q' - Q_o') = -n_q\frac{R}{Z}(P - P_o) - n_q\frac{X}{Z}(Q - Q_o)$$

Comparison of Communication Free Methods

Communication free control	**Advantages**	**Disadvantages**
Conventional Droop	✓ Easy Implementation without communication ✓ High Expandability, modularity and flexibility	✗ Affected By the Physical Parameters ✗ Poor Voltage-Frequency Regulation ✗ Poor Active-Reactive power sharing ✗ Slow Dynamic Response ✗ Poor Harmonic sharing
V(P)/F(Q) droop	✓ Easy Implementation without communication ✓ Better performance for high resistive networks (LV)	✗ Depended on the physical parameters ✗ Poor Voltage-Frequency Regulation ✗ Poor Active-Reactive power sharing
Virtual Impedance	✓ Implementation without communication ✓ Improved power sharing and system stability	✗ Voltage regulation isn't guaranteed ✗ The selection of Virtual Impedance is not straight forward ✗ High Bandwidth design for the controller of the DER
Frame Transformation Method	✓ Implementation without communication ✓ Decoupled Active and Reactive Controls	✗ Difficult to ensure similar transformation for every DG ✗ The physical parameters should be known in advance

Comparison of Communication Free and Communication Based Methods

Primary Control Approach	Advantages	Disadvantages
Communication Based	✓ Accurate Active and Reactive Power sharing ✓ The system parameters should not be known in advance ✓ Good Dynamic Response	✗ Low Reliability (Centralized) ✗ Low Redundancy (New units must be included in the MG control) ✗ Stability affected by Communication Network ✗ High Bandwidth Communication required (increase in costs)
Communication free	✓ Easy Implementation without communication ✓ Modular and Flexible ✓ Assist in the in Plug n Play operation of new units ✓ Resilient against DER outages	✗ Depended on the physical parameters ✗ Less accurate sharing of active and reactive power ✗ Reduced transient performance

- Communication Based methods are more adequate for MG solutions were distances between DER are short (e.g. Microgrids in Building).
- Communication Free methods have significant advantages (low cost, flexibility and modularity) but have performance issues
- More advanced solutions than conventional droop approaches are required for a decentralized primary control of Microgrids.

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Secondary Control of Microgrids

- is responsible for the mitigation of voltage and frequency deviations introduced by primary control.
- can facilitate the synchronization with the upstream network and performs optimal economic management.
- acts on a slower time scale and its computed control outputs are provided to the primary control level.

Secondary control of Microgrids

Secondary control

- The secondary control adjusting voltage/frequency deviations. It ensures the rated frequency and voltage are restored by shifting the operating point up to the nominal value.
- Different control approaches can be categorized according to the scheme of communications implemented.

Communication Based control

- Centralized
- Distributed - Averaging techniques
- Distributed - Consensus techniques

No Communication Based control

- Filter-based
- Estimation-Based

Secondary Control – Communication Based Methods

Secondary Control of Microgrids

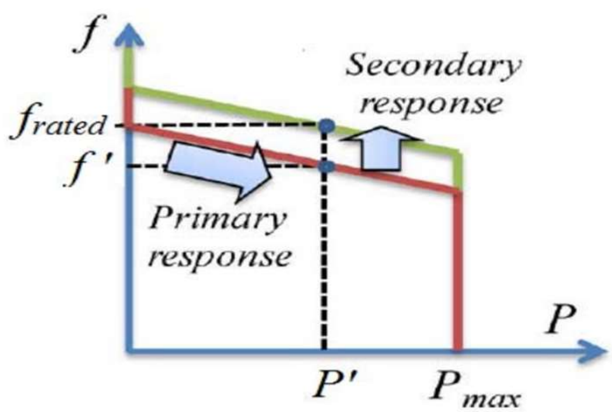
Secondary control

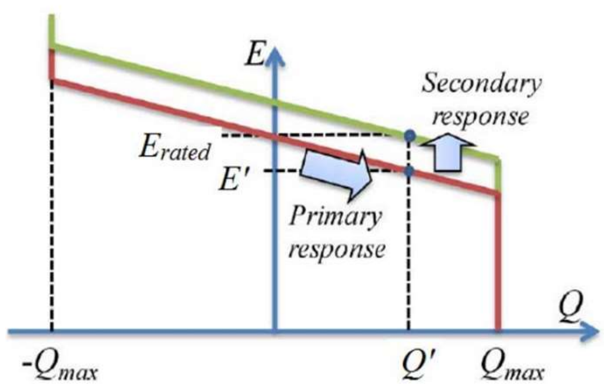
- The control action changes the f_{ref} (V_{ref}) value to compensate for the steady-state error of the primary control action, while maintaining power sharing.
- In contrast with the frequency-active power control loop, where the frequency works as a global steady-state variable, voltage-reactive power control loop could exhibits errors in power-sharing because the voltage is a local output variable of each inverter.

Primary and Secondary controls

$f_i = f^* - m_i P_i + \delta f_i$

$E_i = E^* - n_i Q_i + \delta E_i$

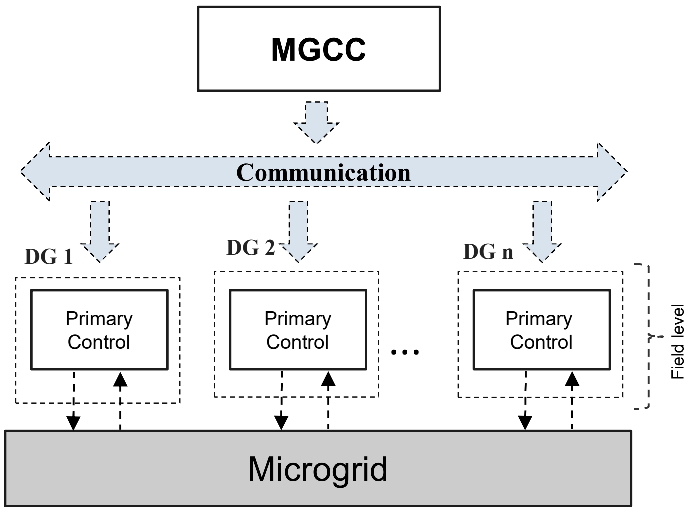




Centralized secondary control

Centralized secondary control

- Conventional centralized secondary control loop is implemented in **MGCC**.
- MGCC gathers the measured data, performs the required calculations, and sends the secondary control terms to each DG periodically.
- **Centrality is useful** for monitoring different aspects of the Microgrid and controlling it as a single entity.
- Extensive communication system is needed but with relatively **low bandwidth**.
- MGCC is not highly reliable since its failure is enough to stop the secondary control action.
- **Reduced scalability**, adding a new unit to the communication system requires updating the setting.



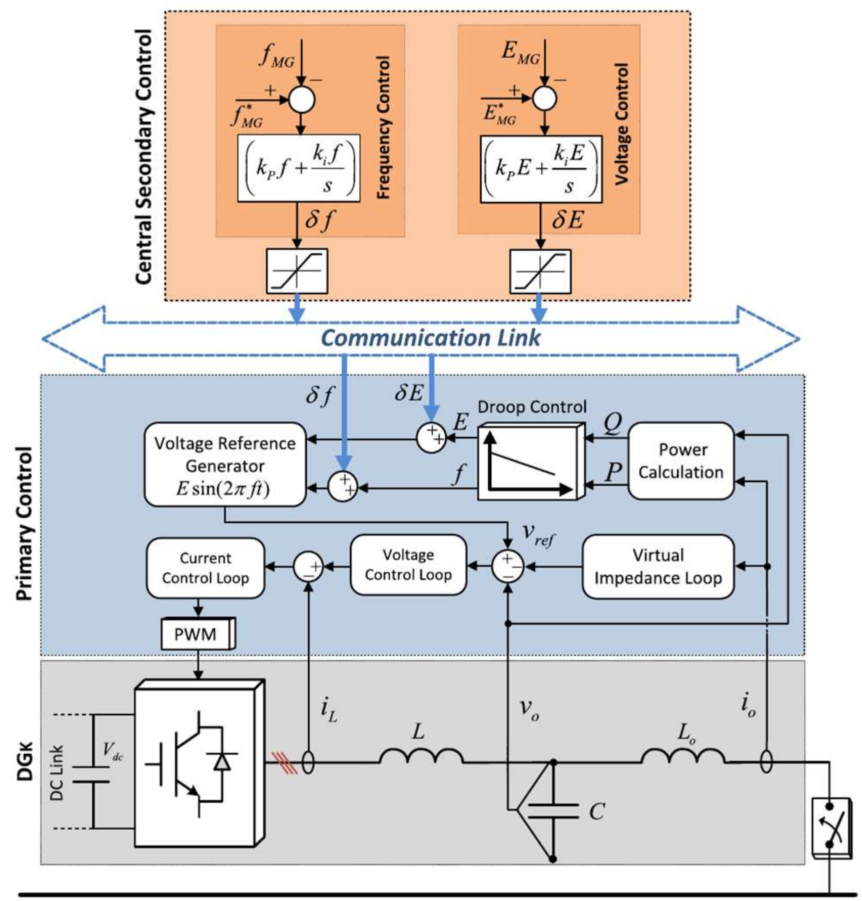
Centralized secondary control

Centralized secondary

- Secondary control loop is is based on a slow **PI control** with a dead band that restores the frequency of the grid when the error is higher than a certain value.
- Commonly, the **control bus** is assigned at the PCC of the MG but other options are available (e.g sensitive load bus).

Secondary control

$$\delta f = K_P(f_{MG}^{*} - f_{MG}) + K_i \int (f^{*} - f_{MG})$$
$$\delta E = K_p(E_{MG}^{*} - E_{MG}) + K_i \int (E^{*} - E_{MG})$$

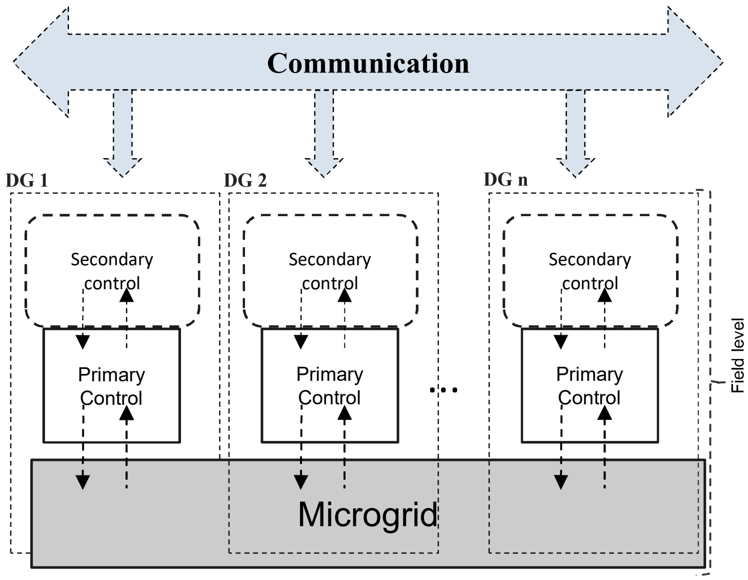


Shafiee et al. - 2014 - Distributed Secondary Control for Islanded Microgrids

Distributed secondary control

Distributed secondary control

- Secondary terms are calculated using **local** and measured variables of other inverters.
- **MGCC is needed**, for coordination of units during black start processes, the tertiary layer, synchronization with the grid etc..
- Fewer layers of the hierarchical control system depend on an MGCC, the control system is more **flexible** and **reliable**.
- Extensive communication system is needed in an **all-to-all communication** scheme
- The failure of one DG unit does not affect the system.



- Well-known secondary layer distributed techniques are cooperative **averaging** and **consensus** techniques.

Averaging Technique

Averaging Technique

- Each converter computes its secondary terms using measured values of all or some of the other inverters.
- Local frequency is measured and sent to all the other inverters to calculate the **average** frequency f_{AVE}.
- Voltage averaging control can be implemented considering not only a voltage restoration term but also a reactive power term, giving independence to the **power-sharing**.

Frequency control

$$\delta f_i = K_P(f_{MG}^* - f_{AVE}) + K_i \int (f_{MG}^* - f_{AVE})$$

$$f_{AVE} = \frac{N}{1}\sum_{N}^{1} f_i$$

Voltage control

$$\delta E = \delta E_{AVE} + \delta Q_{AVE}$$

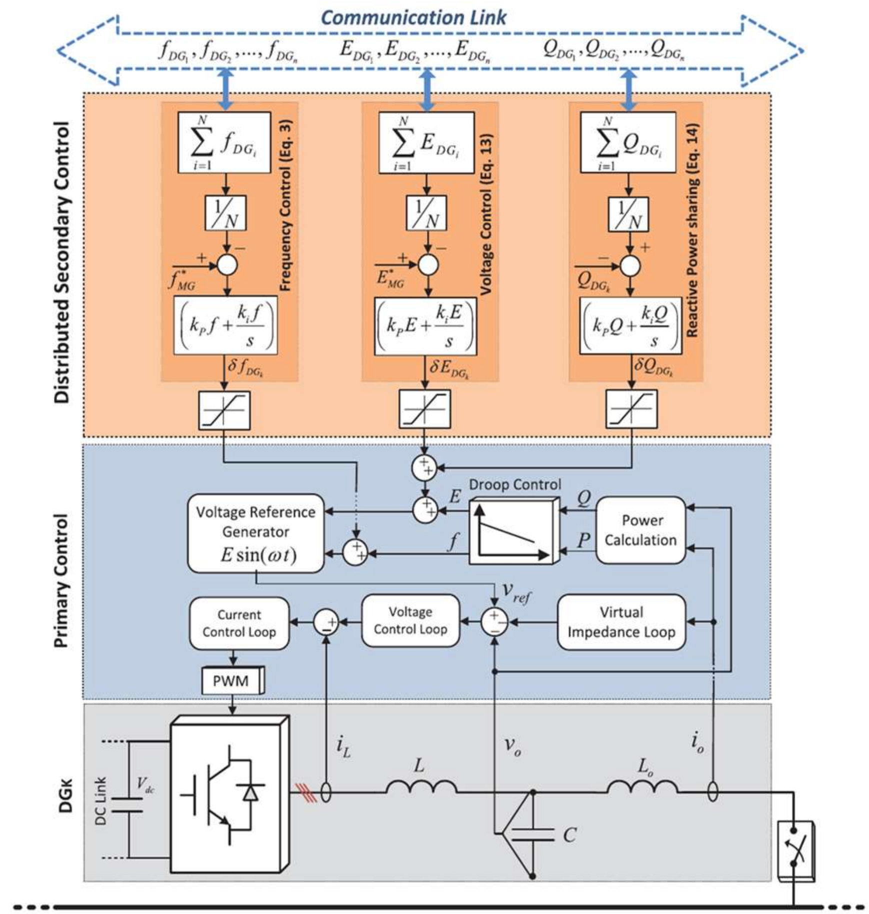
$$\delta E_{AVE} = K_p(E_{MG}^* - E_{AVE}) + K_i \int (E_{MG}^* - E_{AVE})$$

$$\delta Q_{AVE} = K_p(Q_{AVE} - Q_{DG_k}) + K_i \int (Q_{AVE} - Q_{DG_k})$$

Secondary Control - Averaging distributed control

Distributed secondary

- Implement primary and secondary controllers together as a **local controller**.
- Able to restore frequency and voltage of the MG but also ensures reactive **power sharing**.
- **Reliable**, since the secondary control does not rely on a central control.
- **High traffic** data exchange.
- Robust in terms of communication delays and data drop-out.

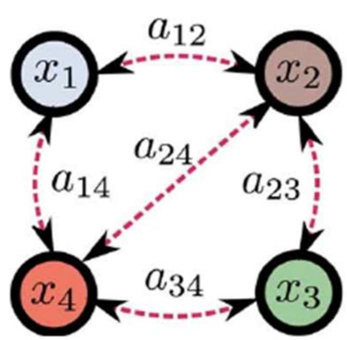


Shafiee et al. - 2014 - Distributed Secondary Control for Islanded Microgrids

Consensus Distributed Control

Consensus Technique

- The main idea is to calculate the secondary terms by an algorithm using **local and transmitted measured signals** and errors.
- **Consensus Regulator Problem** is to find a distributed control protocol for each agent i that drives all states to the same constant steady-state values. This value is known as a **consensus value**.
- To ensure power sharing among all units, the communication network among DGs must be connected.



$$A = \begin{pmatrix} 0 & a_{12} & 0 & a_{14} \\ a_{12} & 0 & a_{23} & a_{24} \\ 0 & a_{23} & 0 & a_{34} \\ a_{14} & a_{24} & a_{34} & 0 \end{pmatrix}$$

Frequency control

$$\omega_i = \omega^* - m_i P_i + \Omega_i$$

$$k_i \frac{dt}{d\Omega_i} = (\omega^* - \omega_i) - \sum_{N}^{j=1} a_{ij}\,(\Omega_i - \Omega_j)$$

Voltage control

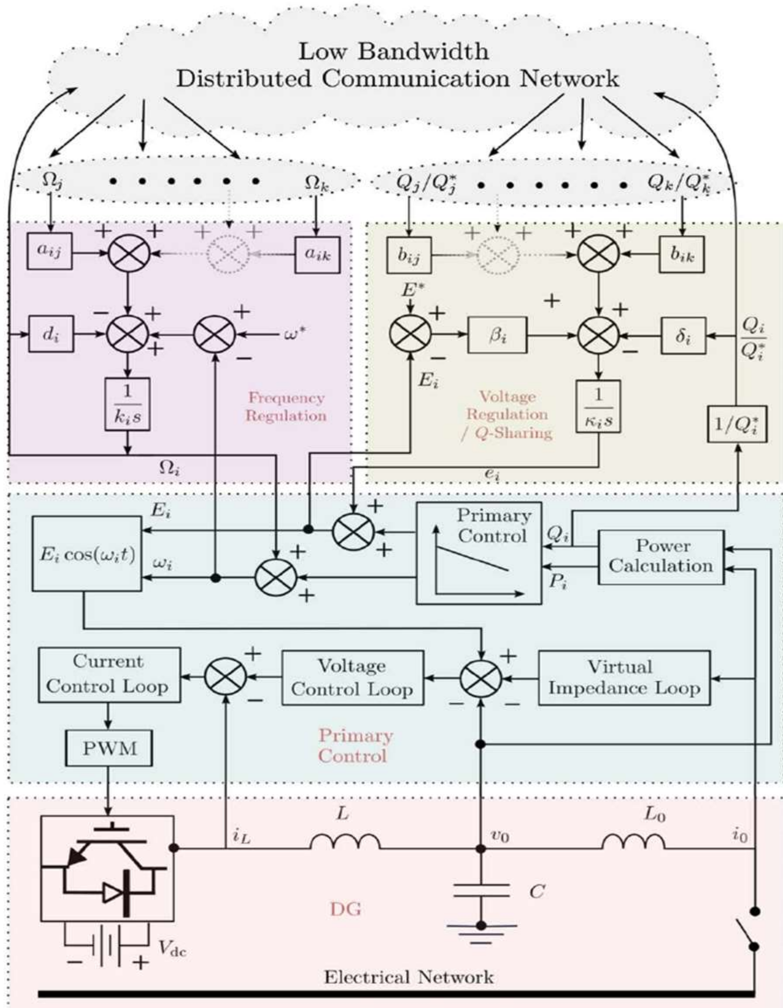
$$E_i = E^* - n_i Q_i + e_i$$

$$k_i \frac{dt}{de_i} = \beta_i (E^* - E) - \sum_{N}^{j=1} b_{ij} \left(\frac{Q_i^*}{Q_i} - \frac{Q_j^*}{Q_j} \right)$$

Secondary control - Consensus Distributed Control

Consensus distributed control

- Able to restore frequency and voltage of the MG but also ensures reactive **power sharing**.
- No prior knowledge of the system is required - **adaptable** to different microgrid topologies
- Good behavior even in **non-ideal** communication scenarios.
- High **dependence** on the communication infrastructure. - communication topology may get complex when the number of DGs increase.



;e Control of Islanded Microgrids via Distributed Averaging

Secondary Control – Communication Free Methods

Decentralized Secondary Control

Filter based techniques

- Calculate of secondary control exclusively with local measurements and predefined references without any communication.
- The main idea lies on **decoupling the dynamics** of the primary and the secondary control loops. It facilitates their individual designs by giving them different transient responses.
- Typically, a suitable **filter** is applied for the calculation of secondary terms.

Primary and secondary decentralized controls

$$f = f^* - m_i P + LPF \cdot (f^* - f)$$
$$E = E^* - n_i Q + LPF \cdot (E^* - E)$$

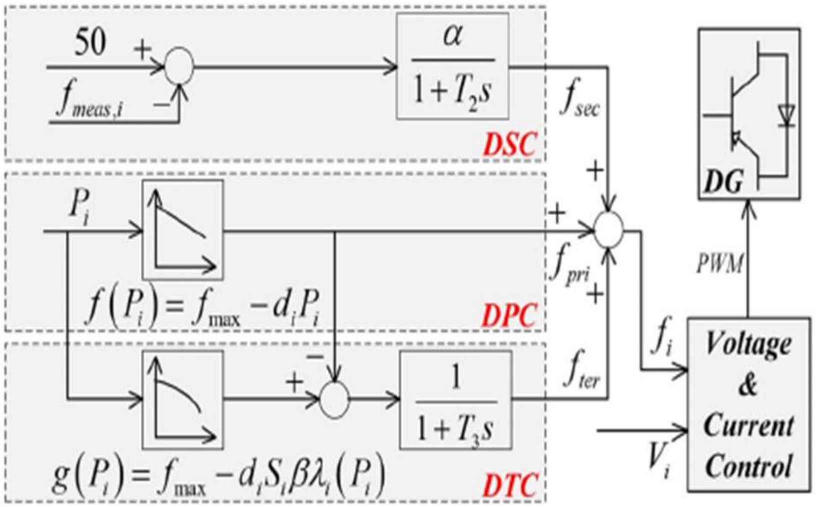
Washout filter

$$f = f^* - \frac{S + K_p}{m_p S}(P - P^*)$$
$$E = E^* - \frac{S + K_q}{n_q S}(Q - Q^*)$$

Decentralized Secondary Control – Filter Based Techniques

Filter based techniques

- Provides flexibility and **plug-and-play** capability.
- Voltage control, requires the **pre-study of the topology** and loads of the grid for accurate power sharing.
- There is an inherent **trade-off** between speed of response and accuracy.
- Challenges are related to the **stability**, modeling, and **robustness.**

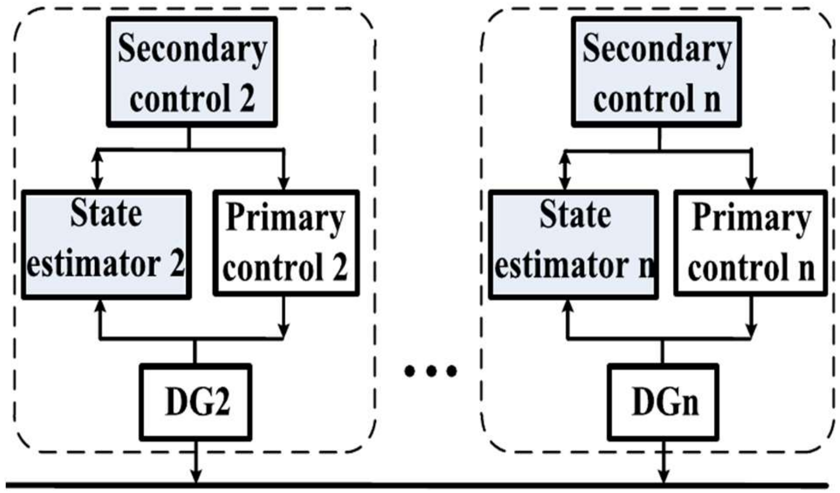


Huanhai Xin et al. - 2015 - Control of Island AC Microgrids Using a Fully Distributed Approach

Decentralized Secondary Control – Estimation Based Techniques

Estimation-Based techniques

- A state estimator is designed and localized in each DG unit to obtain the dynamic responses of the other DG units.
- State estimators are **model based**, designed on the basis of the dynamic MG model.
- Accurate reactive power sharing and voltage restoration.
- **Sensitive** to model inacuraccies.
- Observability is not guaranteed.



Conclusions

- Microgrids are Structures ideal to coordinate the Distributed Energy Resources at Distribution Networks
- Key for the decentralization of Power System Control that in collaboration with large centralized transmission systems is essential to face the current system challenges
- Microgrids control is a very active area of research in the last years
- Various techniques have been developed for all hierarchical levels of control covering centralized, distributed and decentralized approaches
- Advanced promising techniques include Model Predictive Control, Reinforcement Learning Methods, Cooperative and Non-Cooperative Methods, etc.

National Technical
University of Athens

SMART RUE smartgrids Research Unit ECE NTUA

Thank you for your attention!

Nikos Hatziargyriou
nh@power.ece.ntua.gr

A. Vassilakis, D. Lagos, F. Paleogiannis, A. Kontou,
P. Kotsampopoulos, A. Dimeas ….