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Energy Management

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1. Introduction

Fossil fuels are currently the major source of energy in the world. However, as the world is considering more economical and environmentally friendly alternative energy generation systems, the global energy mix is becoming more complex. Factors forcing these considerations are (a) the increasing demand for electric power by both developed and developing countries, (b) many developing countries lacking the resources to build power plants and distribution networks, (c) some industrialized countries facing insufficient power generation and (d) greenhouse gas emission and climate change concerns. Renewable energy sources such as wind turbines, photovoltaic solar systems, solar-thermo power, biomass power plants, fuel cells, gas micro-turbines, hydropower turbines, combined heat and power (CHP) micro-turbines and hybrid power systems will be part of future power generation systems.

A new trend in power systems is developing toward distributed generation (DG), which means that energy conversion systems (ECSs) are situated close to energy consumers and large units are substituted by smaller ones. For the consumer the potential lower cost, higher service reliability, high power quality, increased energy efficiency, and energy independence are all reasons for interest in distributed energy resources (DERs). The use of renewable distributed energy generation and "green power" can also provide a significant environmental benefit. This is also driven by an increasingly strained transmission and distribution infrastructure as new lines lag behind demand and to reduce overall system losses in transmission and distribution. Other motives are the increased need for reliability and security in electricity supply, high power quality needed by an increasing number of activities requiring UPS like systems and to prevent or delay the expansion of central generation stations by supplying the growing loads locally (McDowall 2007; Brabandere October, 2006).

Nevertheless, all of these sources require interfacing units to provide the necessary crossing point to the grid. The core of these interfacing units is power electronics technologies since they are fundamentally multifunctional and can provide not only their principle interfacing function but various utility functions as well. The inverter is considered an essential component at the grid side of such systems due to the wide range of functions it has to perform. It has to convert the DC voltage to sinusoidal current for use by the grid in addition to act as the interface between the ECSs, the local loads and the grid. It also has to handle the variations in the electricity it receives due to varying levels of generation by the renewable energy sources (RESs), varying loads and varying grid voltages. Inverters influence the frequency and the voltage of the grid and seem to be the main universal modular building block of future smart grids mainly at low and medium voltage levels.

The main problem associated with that is the development of general, flexible, integrated, and hierarchical control strategy for DERs to be integrated into the dynamic grid control and management procedures of electrical power supply systems (primary control, frequency and power control, voltage and reactive power control) through flexible power electronics namely inverters.

2. Distributed Generation

Currently, there is no consensus on how the distributed generation (DG) should be exactly defined (Purchala, Belmans et al. 2006). A very good overview of the different definitions proposed in the literature is given in (Pepermans, Driesen et al. 2005). In general, distributed generation describes electric power generation that is geographically distributed or spread out across the grid, generally smaller in scale than traditional power plants and located closer to the load, often on customers' property. Distributed generation is characterized by some or all of the following features:

- Small to medium size, geographically distributed power plants
- Intermittent input resource, e.g., wind, solar
- Stand-alone or interface at the distribution or sub-transmission level
- Utilize site-specific energy sources, e.g., wind turbines require a sustained wind speed of 20 km/hour. To meet this requirement they are located on mountain passes or the coast
- Located near the loads
- Integration of energy storage and control with power generation

Technologies those are involved in Distributed Generation include but are not limited to: Photovoltaic, Wind energy conversion systems, Mini and micro hydro, Geothermal plants, Tidal and wave energy conversion, Fuel cell, Solar-thermal-electric conversion, Biomass, Micro and mini turbines, Energy storage technologies, including flow and regular batteries, pump-storage hydro, flywheels and thermal energy storage.
The idea behind DG is not a new concept. In the early days of electricity generation, DG was the rule, not the exception (Driesen and Belmans 2006). However, technological evolutions and economical reasons developed the current system with its huge power generation plants, transmission and distribution grids. An overview of Distributed Generation is illustrated in Fig. 1.2.
In the last decade, technological innovation, economical reasons and the environmental policy renew the interest in Distributed Generation. The major reasons for that are:

- To reduce dependency on conventional power resources
- To reduce emissions and environmental impact
- Market liberalization
- Improve power quality and reliability

- Progress in DG technologies especially RESs
- To reduce transmission costs and losses
- To increase system security by distributing the energy plants instead of concentrating them in few locations making them easy targets for attacking

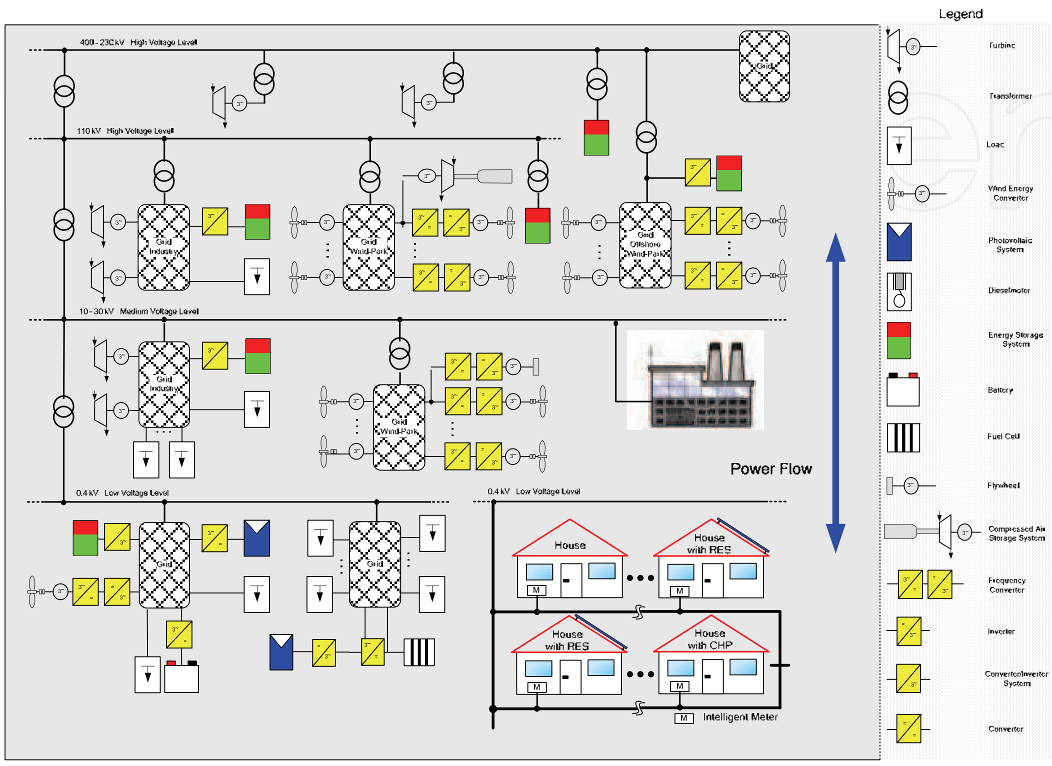

Fig. 1. Principal supply strategy of distributed Generation.

Distributed generation is becoming an increasing important part of the power infrastructure and the energy mix and is leading the transition to future Smart Grids. This is as well one of European Commission targets in order to increase the efficiency, safety and reliability of European electricity transmission and distribution systems and to remove obstacles to the large-scale integration of distributed and renewable energy sources.

3. Future Power Supply Systems (Smart Grids)

Energy plays a vital role in the development of any nation. The current electricity infrastructure in most countries consists of bulk centrally located power plants connected to highly meshed transmission networks. However, new trend is developing toward distributed energy generation, which means that energy conversion systems (ECSs) will be situated close to energy consumers and the few large units will be substituted by many smaller ones. For the consumer the potential lower cost, higher service reliability, high power quality, increased energy efficiency, and energy independence are all reasons for the increasing interest in what is called "Smart Grids".

Although the "Smart Grid" term was used for a while, there is no agreement on its definition. It is still a vision, a vision that is achievable and will turn into reality in near future. One of the best and general definitions of a smart grid is presented in (Energy 2007). Smart grid is an intelligent, auto-balancing, self-monitoring power grid that accepts any source of fuel (coal, sun, wind) and transforms it into a consumer's end use (heat, light, warm water) with minimal human intervention. It is a system that will allow society to optimize the use of RESs and minimize our collective environmental footprint. It is a grid that has the ability to sense when a part of its system is overloaded and reroute power to reduce that overload and prevent a potential outage situation; a grid that enables real-time communication between the consumer and utility allowing to optimize a consumer's energy usage based on environmental and/or price preferences (Energy 2007).

3.1 Drivers Towards Smart Grids

Many factors are influencing the shape of our future electricity networks including climate change, aging infrastructure and fossil fuels running out. According to the International Energy Agency (IEA) Global investments required in the energy sector for 2003-2030 are an estimated $16 trillion. In Europe alone, some €500 billion worth of investment will be needed to upgrade the electricity transmission and distribution infrastructure. The following are the main drivers towards Smart Grids (Hatziagyriou 2008; Ipakchi 2007):

- ***The Market:*** Providing benefits to the customers by increasing competition between companies in the market. Competition has led many utilities to divest generation assets, agree to mergers and acquisitions, and diversify their product portfolios. This will give the customers a wider choice of services and lower electricity prices.
- ***Environmental regulations:*** Another significant driver concerns the regulation of the environmental, public health, and safety consequences of electricity production, delivery, and use. The greenhouse gases contribute to climate change, which is recognised to be one of the greatest environmental and economic challenges facing humanity. To meet these environmental policies, rapid deployment of highly effective, unobtrusive, low-environmental-impact grid technologies is required.
- ***Lack of resources:*** Energy is the main pillar for any modern society. Countries without adequate reserves of fossil fuels are facing increasing concerns for primary energy availability. Currently approximately 50% within EU is imported from politically unstable countries.
- ***Security:*** The need to secure the electric system from threats of terrorism and extreme weather events are having their effect as well. Techniques must exist for identifying occurrences, restoring systems quickly after disruptions, and providing services during public emergencies. This is why electricity grids should be redesigned to cope with the new rule.
- ***Aging infrastructure:*** The aging infrastructure (Europe and USA) of electricity generation plants, transmission and distribution networks is increasingly threatening security, reliability and quality of supply. The most efficient way to solve this is by integrating innovative solutions, technologies and grid architectures.
- ***New generation technologies (Distributed Generation):*** These forms of generation have different characteristics from traditional plants. Apart from large wind farms and large hydropower plants, this type of generation tends to have much smaller

electricity outputs than the traditional type. Some of the newer technologies also exhibit greater intermittency. However, existing transmission and distribution networks, were not initially designed to incorporate these kinds of generation technology in the scale that is required today.

- ***Advanced power electronics:*** Power electronics allow precise and rapid switching of electrical power. Power electronics are at the heart of the interface between energy generation and the electrical grid. This power conversion interface-necessary to integrate direct current or asynchronous sources with the alternating current grid-is a significant component of energy systems.
- ***Information and communication technologies (ICT):*** The application of ICT to automate various functions such as meter reading, billing, transmission and distribution operations, outage restoration, pricing, and status reporting. The ability to monitor real-time operations and implement automated control algorithms in response to changing system conditions is just beginning to be used in electricity (2003). Distributed intelligence, including "smart" appliances, could drive the co-development of the future architecture.

3.2 Key Challenges for Smart Grids

Even though many drivers for smart grids and their benefits are obvious, there are many challenges and barriers standing in the way and should be cracked first. These include:

- ***Standardisation:*** Design and development of a modular standardised architecture of modern power electronic systems for linking distributed energy converting systems (DECSs) (i.e. PV, wind energy converters, fuel cells, diesel generators and batteries) to conventional grids and to isolated grids on the basis of modular power electronic topologies which fulfil the requirements for integration into the dynamic control system of the grid (Ortjohann and Omari 2004).
- ***Advance communication layer:*** Development and implementation of a general communication layer model for simple and quick incorporation of DECSs in the grid and its superimposed online control system
- ***Non-technical challenges:*** Issues such as pricing, incentives, decision priorities, risk responsibility and insurance for new technologies adaptation, interconnection standards, regulatory control and addressing barriers. This also includes, finding a profitable business model, attracting resources and developing better public policies (Nigim and Lee 2007).

4. State of the Art

This section presents the state-of-the-art of power electronic inverters control used currently in electrical systems. Different system architectures, their modes of operation, management and control strategies will be analysed. Advantages and disadvantages will be discussed. Though, it is not easy to give a general view at the state of the art for the research area since it is rapid and going in different directions. The focus here will be on the main streams in low voltage grids especially paralleled power electronics inverters. Inverters are often paralleled to construct power systems in order to improve performance or to achieve a high system rating. Parallel operation of inverters offers also higher reliability over a single centralized source because in case one inverter fails the remained (n-1) modules can deliver the needed power to the load. This is as well driven by the increase of RESs such as photovoltaic and wind. There are many techniques to parallel inverters which are already suggested in the literature, they can be categorized to the following main approaches:

1) Master/Slave Control Techniques
2) Current/Power Deviation (Sharing) Control Techniques
3) Frequency and Voltage Droop Control Techniques
   a) Adopting Conventional Frequency/Voltage Droop Control
   b) Opposite Frequency/Voltage Droop Control
   c) Droop Control in Combination with Other Methods

4.1 Master/Slave Control Techniques

The Master/Slave control method uses a voltage controlled inverter as a master unit and current controlled inverters as the slave units. The master unit maintains the output voltage sinusoidal, and generates proper current commands for the slave units (Prodanovic, Green et al. 2000; Tuladhar 2000; Ritwik Majumder , Arindam Ghosh et al. 2007).
One of the Master/Slave configuration is the scheme suggested in (Chen, Chu et al. 1995; Jiann-Fuh Chen and Chu 1995) , see Fig. 2, which is a combination of voltage-controlled and current-controlled PWM inverters for parallel operation of a single-phase uninterruptible power supply (UPS). The voltage-controlled inverter (master) is developed to keep a constant sinusoidal wave output voltage. The current-controlled inverter units are operated as slave controlled to track the distributive current. The inverters do not need a PLL circuit for synchronization and gives a good load sharing. However, the system is not redundant since it has a single point of failure.

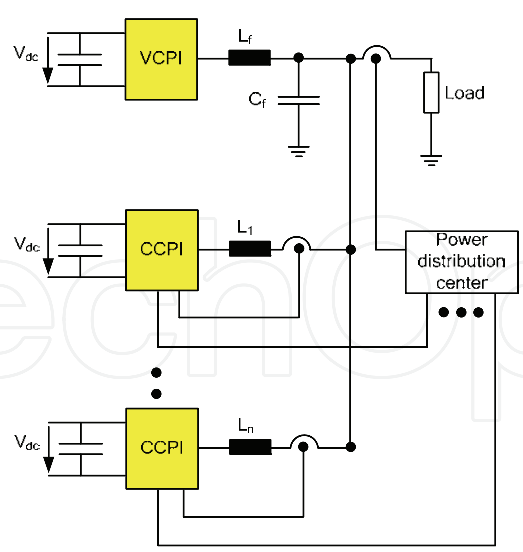

Fig. 2. Combined voltage and current controlled inverters (Jiann-Fuh Chen and Chu 1995).

A comparable scheme is also presented in (K Siri, C.Q. Lee et al. 1992) but it needs even more interconnection since it is sharing the voltage and current signals. In (Holtz and Werner 1990) the system is redundant by extended monitoring of the status and the

operating conditions of all power electronic equipment. Each block of the UPS system is monitored by two independent microcomputers that process the same data. The microcomputers are part of a redundant distributed monitoring system that is separately interlinked by two serial data buses through which they communicate. They establish a hierarchy among the participating blocks by defining one of the healthy inverter blocks as the master.
The scheme proposed in (Petruzziello 1990), see Fig. 3., is based on the Master/Slave configuration but is using a rotating priority window which provides random selection of a new master and therefore results in true redundancy and increase reliability.

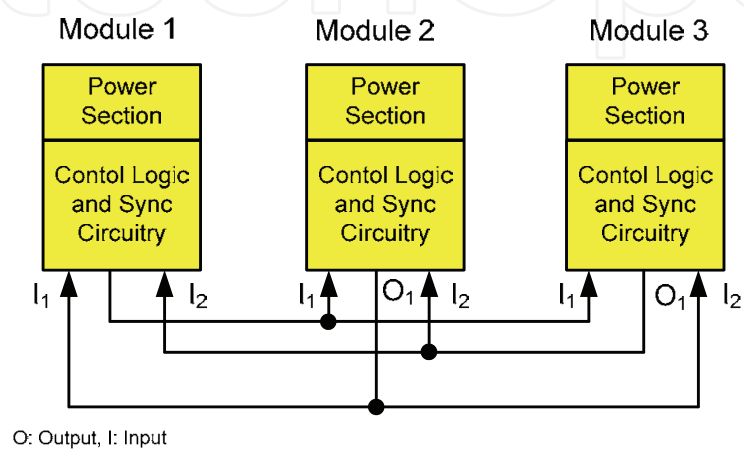

Fig. 3. Proposed Master/Slave configuration in (Petruzziello 1990)

In (Van Der Broeck and Boeke 1998) the system is also redundant since a status line is used to decide about the master inverter using a logical circuit (flip-flop), if the master is disconnected one slave becomes automatically the master. The auto-master-slave control presented in (Pei, Jiang et al. 2004) is designed to let the unit with highest output real power act as a master of real power and derives the reference frequency, the others have to follow as slaves. The regulation of the reactive power is similar, the highest output reactive power module acts as master of reactive power and adjusts the voltage reference amplitude.
In (Lopes 2004; J.A.P.Lopes, Moreira et al. 2006) the paper focus on operation of the microgrid when it becomes isolated under different condition. This was investigated for two main control strategies, single master operation where a voltage source inverter (VSI) can be used as voltage reference when the main power supply is lost; all the other inverters can then be operated in PQ mode. And multi-master operation where more than one inverter are operated as a VSI, other PQ inverters may also coexist. In more recent papers (Prodanovic, Green et al. 2000; T.C. Green and Prodanovic 2007; Prodanovic Oct. 2006) an enhanced approach is introduced, the master inverter is replaced by a central control block which controls the output voltages and can influence the output current of the different units, this is sometimes called central mode control or distributed control. This means that the voltage magnitude, frequency and power sharing are controlled centrally (commands are distributed through a low bandwidth communication channels to the inverters) and other issues such as harmonic suppression are done locally, see Fig. 4.

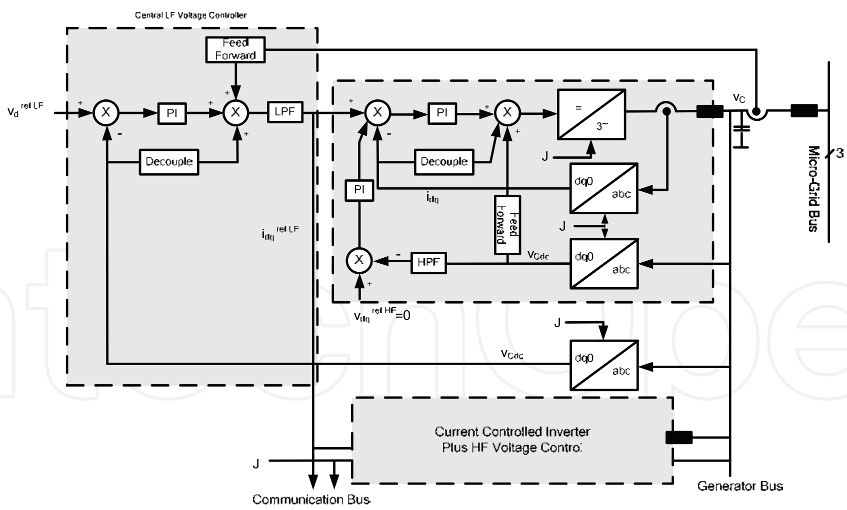

Fig. 4. Proposed distributed control configuration in (T.C. Green and Prodanovic 2007).

4.2 Current/Power Deviation (Sharing) Control Techniques

In this control technique the total load current is measured and divided by the number of units in the system to obtain the average unit current. The actual current from each unit is measured and the difference from the average value is calculated to generate the control signal for the load sharing (Tuladhar 2000). In the approach suggested in (T.Kawabata and S.Higashino 1988), see Fig. 5, the voltage controller adjusts the small voltage deviation and keeps the voltage constant. The ΔI signal is detected and given to the current loop as a correction factor, and the ΔP signal controls the phase of the reference sine wave. A very good load sharing can be obtained. Transient response is very good due to the feed forward control signal (Tuladhar 2000).

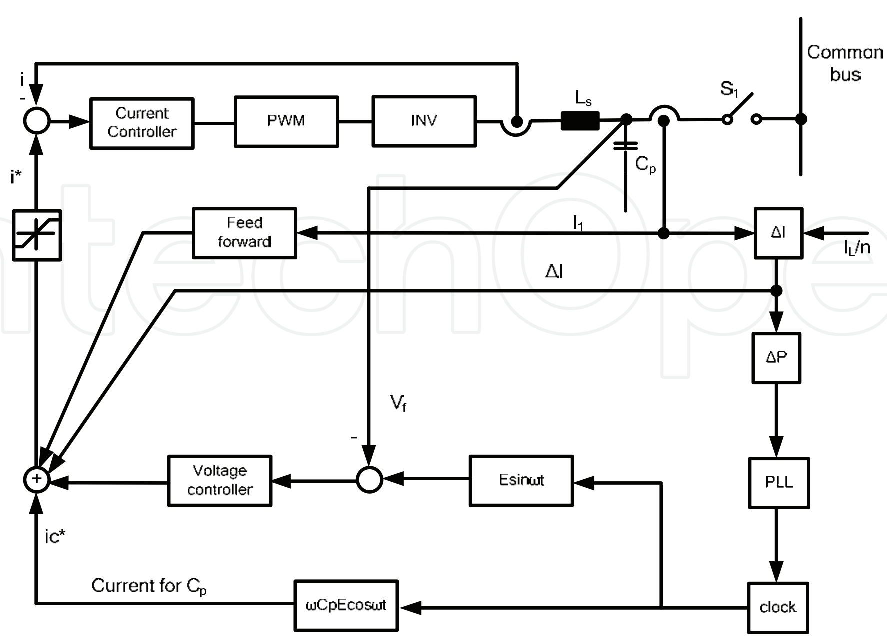

Fig. 5. Proposed parallel operation of inverter with current minor loop (T.Kawabata and S.Higashino 1988).

In (Huang 2006) circular chain control (3C) strategy is proposed, see below Fig. 6., all the modules have the same circuit configuration, and each module includes an inner current loop and an outer voltage loop control. With the 3C strategy, the modules are in circular chain connection and each module has an inner current loop control to track the inductor current of its previous module, achieving an equal current distribution.

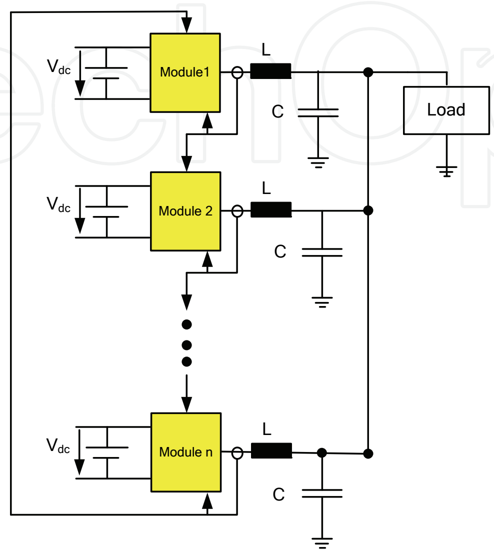

Fig. 6. The proposed circular chain control (3C) strategy (Huang 2006).

Authors of (Hanaoka 2003) proposed an inverter current feed-forward compensation which makes the output impedance resistive rather than inductive in order to get a precise load sharing. In (Hyun 2006) the paper goes further based on the approach introduced in (Hanaoka 2003) and proposes a solution to the noise problem of harmonic circulating currents due to PWM non-synchronization which is affecting the load sharing precision. This is done in (S. Tamai 1991) using a digital control algorithm. The digital voltage controller, which has high-speed current control as a minor loop, provides low voltage distortion even for nonlinear loads. Output current of each UPS module is controlled to share the total load current equally and the voltage reference command of each inverter is controlled to balance the load current. In (H.Oshima, Y.Miyazaya et al. 1991; W.Hoffmann, R.Bugyi et al. 1993; Lee, Kim et al. 1998) similar approaches are suggested. In (Qinglin, Zhongying et al. 2006) the focus is on developing a solution for the effect of DC offset between paralleled inverters and its effect on the circulating currents. In (Xing, Huang et al. 2002) the authors suggest two-line share bus connecting all inverters, one for current sharing control and the other to adjust the voltage reference.

4.3 Frequency and Voltage Droop Control Techniques

Many methods were found in the literature and can be roughly categorized into the following:

a. Adopting Conventional Frequency/Voltage Droop Control
b. Opposite Frequency/Voltage Droop Control
c. Droop Control in Combination with Other Methods

a. Adopting Conventional Frequency/Voltage Droop Control

In (C.-C. Hua) the paper proposes a control technique for operating two or more single phase inverter modules in parallel with no auxiliary interconnections. In the proposed parallel inverter system, each module includes an inner current loop and an outer voltage loop controls, see Fig. 7. This technique is similar to the conventional frequency/voltage droop concept; uses frequency and fundamental voltage droop to allow all independent inverters to share the load in proportion to their capacities.

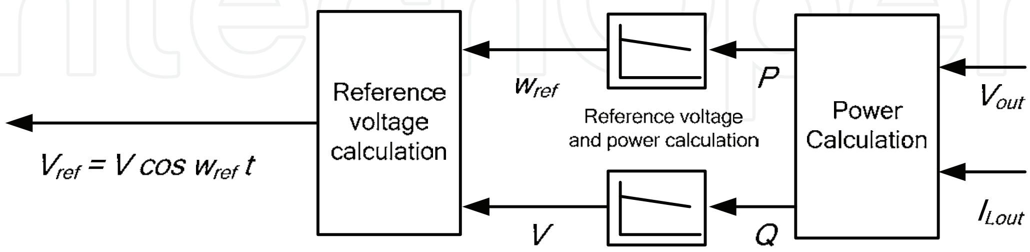

Fig. 7. Reference voltage and power calculation (C.-C. Hua).

In (M. C. Chandorkar 1993) scheme for controlling parallel-connected inverters in a stand-alone AC supply system is presented, see Fig. 8. This scheme is suitable for control of inverters in distributed source environments such as in isolated AC systems, large and UPS systems, PV systems connected to AC grids. Active and reactive power sharing between inverters can be achieved by controlling the power angle (by means of frequency), and the fundamental inverter voltage magnitude. Simulation results obtained for large units using Gate turn-off (GTO) thyristor switches. The control is done in the d-q reference frame; an inverter flux vector is formed by integrating the voltage space vector. The choice of the switching vectors is essentially accomplished by hysteresis comparators for the set values and then using a look-up table to choose the correct inverter output voltage vector. The considerations for developing the look-up table are dealt with in (Noguchi 1986). However, the inductance connected between the inverter and the load makes the output impedance high. Therefore, the voltage regulation as well as the voltage waveform quality is not good under load change conditions as well as a nonlinear load condition. The authors explain the same concept but with focusing in control issues of UPS systems in (M. C. Chandorkar, Divan et al. 1994).

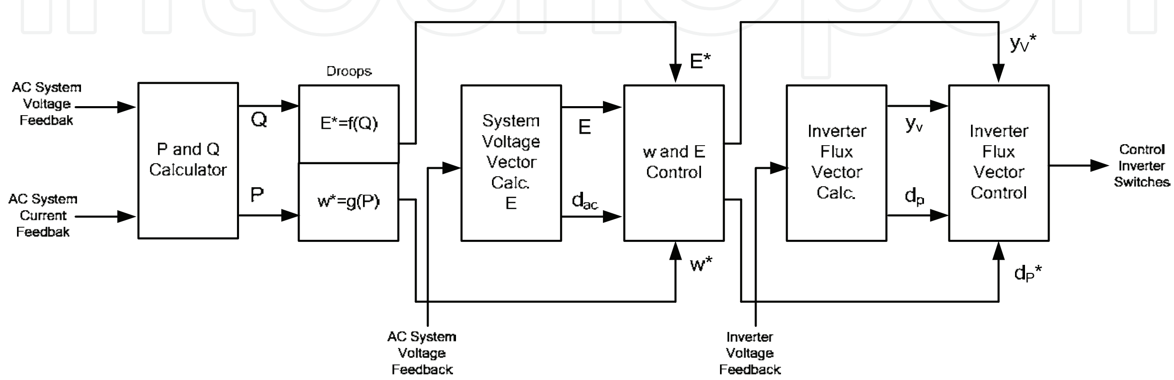

Fig. 8. Inverter control scheme (M. C. Chandorkar 1993).

In (Hauck Matthias 2000; Matthias and Helmut 2002) the inverse droop equations are used to control the inverter, see Fig. 9. The inverter is able to work in parallel with a constant-voltage constant-frequency system, as well as with other inverters or also in stand-alone mode. There is no communication interface needed. The different power sources can share the load also under unbalanced conditions. Very good load sharing is achieved by using an outer control loop with active and reactive power controller, for which the set point variables are derived out of droops. Furthermore, a relatively big inductance is used in the LC filter and a small decoupling reactance is used to decouple the inverter from other voltage sources. The interface inductance make the voltage source converters (VSCs) less sensitive to disturbances on the load bus (M. Chandorkar 1994; Sao and Lehn 2005).

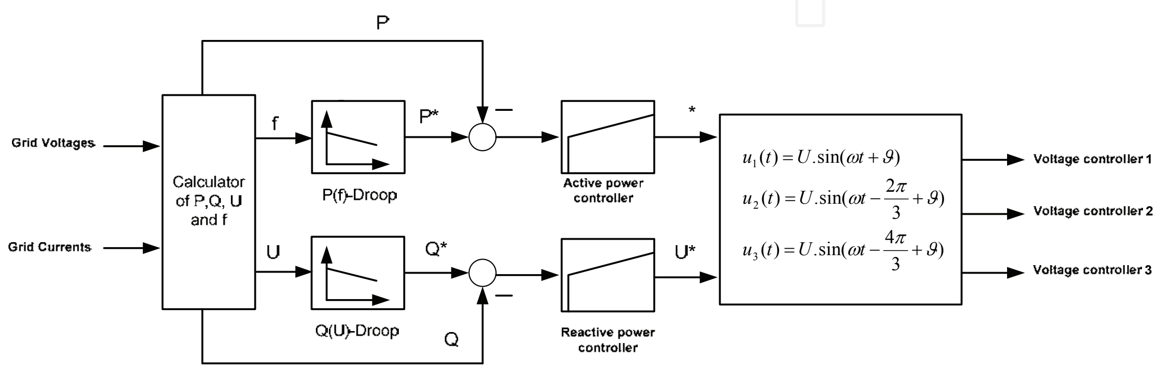

Fig. 9. Inverter control scheme proposed in (Hauck Matthias 2000; Matthias and Helmut 2002).

In (C.K. Sao) an interesting autonomous load-sharing technique for parallel connected three-phase voltage source converters is presented. This paper focuses on an improvement to the conventional frequency droop scheme for real power sharing and the development of a new reactive power-sharing scheme. The improved frequency droop scheme computes and sets the phase angle of the VSC instead of its frequency. It allows the operator to tune the real power sharing controller to achieve desired system response without compromising frequency regulation by adding an integral gain into the real power control. The proposed reactive power sharing scheme introduces integral control of the load bus voltage, combined with a reference that is drooped against reactive power output. This causes two VSCs on a common load bus to share the reactive load exactly in the presence of mismatched interface inductors if the line impedances are much smaller than the interface reactors (assuming short lines). Moreover, in the proposed reactive power control, the integrator gain can be varied to achieve the desired speed of response without affecting voltage regulation.
In (Engler 2000; A. Engler, M. Meinh et al. 2003; A. Engler, M. Meinhardt et al. 2004) the author discusses the application of conventional droops for voltage source inverters and categorize the system components to form a modular AC-hybrid power system. Then in (Engler 2006) by the same author an investigation of what is called opposite droop (active power/voltage and reactive power/frequency droop) control is carried out. The focus is on the need of different droop functions for different types of grids. In (Engler 2006) it is found that for high voltage (mainly inductive) grids the regular droop functions can be used also for distributed generation systems. For low voltage (mainly resistive) grids, so-called opposite droop functions could be used instead but the regular droop functions are advantageous since it allows connectivity to higher voltage levels and power sharing also

with rotating generators (A. Engler and Soultanis; Engler 2005; Karlsson, Björnstedt et al. 2005; Engler 2006).
A microgrid control was introduced and implemented in (Lasseter 2002; Robert Lasseter and Piagi 2006; Lasseter 2007; Piagi and Lasseter June 2006), the microgrid has two critical components, the static switch and the micro-source. The static switch has the ability to autonomously island the microgrid from disturbances such as faults or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid insuring a transient free operation without having to match frequency and phase angles at the connection point. Each micro-source can seamlessly balance the power on the islanded microgrid using a power vs. frequency droop controller. This frequency droop also insures that the microgrid frequency is different from the grid to facilitate reconnection to the utility. The introduced micro-source control is shown in Fig. 10.

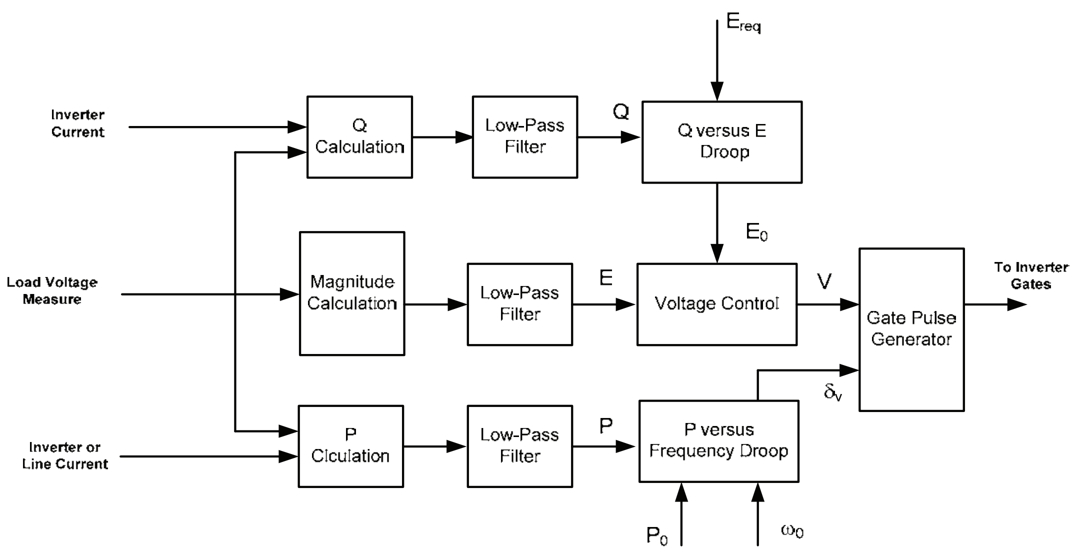

Fig. 10. Inverter control scheme proposed in (Lasseter 2002; Robert Lasseter and Piagi 2006; Lasseter 2007; Piagi and Lasseter June 2006).

The authors of (Ritwik Majumder , Arindam Ghosh et al. 2007) present a scheme for controlling parallel connected inverters using droop sharing method in a standalone ac system. The scheme proposed a PI regulator to determine the set points for generator angle and flux. The dynamic response of the system is investigated under different impedance load conditions especially motor loads. Paper (Maria Brucoli and Green 2006) analyzes the fault behaviour of four wire paralleled inverters (in droop mode) based on their control methodology.

b. Opposite Frequency/Voltage Droop Control

In (Karlsson, Björnstedt et al. 2005; Guerrero, Berbel et al. 2006) the method selected here is to modify the droop functions of the source converters so that the regular droop functions are used in the steady-state case and opposite droops are used in transients, see Fig. 11. Note that here $\omega_{ref} = \omega_n$ and $v_{ref} = V_n$. The steady-state droop functions are according to:

$$p_s^{\,*} = K_\omega(\omega_{ref} - \omega) \tag{1}$$

$$q_s^{\,*} = K_v(v_{ref} - v_q) \tag{2}$$

where p_S^* and q_S^* are the active and reactive power references (index s denotes source converter, e.g. unit 1). K is the droop gain (slope). For the transient droop functions according to:

$$p_s^{\,*} = K_v(v_{ref} - v_q) \tag{3}$$

$$q_s^{\,*} = -K_\omega(\omega_{ref} - \omega) \tag{4}$$

where $\omega_{ref} = \omega^*$ and $v_{ref} = v^*$

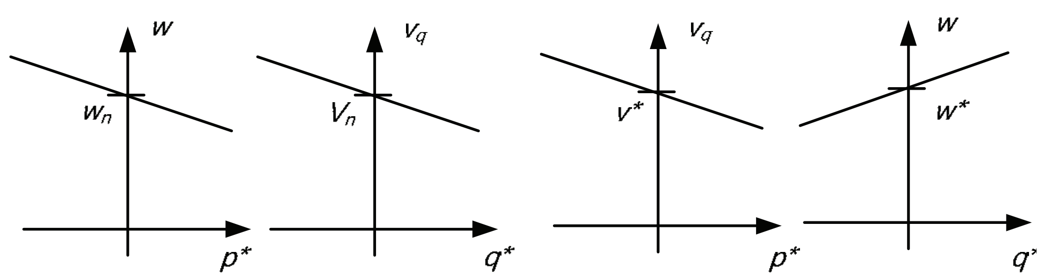

Fig. 11. Conventional droop functions (left) and transient droop functions (right) (Karlsson, Björnstedt et al. 2005; Guerrero, Berbel et al. 2006).

In this method the load-sharing is acceptable for the investigated, highly resistive, network. Still, in the case of line inductance in the same order of magnitude as the converter output filter inductance there can be a considerable degradation of power quality in terms of voltage disturbance. The origin of this degradation is the LC-circuit formed by the line inductance and the converter AC side capacitors. Furthermore, using this approach it is not possible to connect with the high level voltage which is using the regular conventional droop functions. In (Guerrero J.M, García de Vicuña et al. 2003; Guerrero, Vicuña et al. 2004; Guerrero, Berbel et al. 2006; Guerrero 2006; Guerrero 2005) the authors focus on the transient behaviour of parallel connected UPS inverters, they claim that damping and oscillatory phenomena of phase shift difference between the paralleled inverters could cause instabilities, and a large transient circulating current that can overload and damage the paralleled inverters. To overcome this they proposed using a method called "droop/boost" control scheme which adds integral-derivative terms to the droop function. This can be seen in Fig. 12. Stable steady-state frequency and phase and a good dynamic response are obtained. Further, virtual output impedance is proposed in order to reduce the line impedance impact and to properly share nonlinear loads, this is done using a high pass filter, the filter gain and pole values of this must be carefully chosen. Furthermore, the test results shown are considering a short resistive line, but the method is not taking into consideration what happens if the distance between the inverters is considerable, which is normally the case in distributed generation were an inductive impedance component appears. Nevertheless, when an inverter is connected suddenly to the common AC bus, a current peak appears due to the initial phase error (Guerrero 2006). Compatibility problems are expected because of the opposite droop scheme (if synch generator will be included). The characteristic and the scheme are shown below:

$$E = E^* - nP - n_d \frac{dP}{dt} \tag{5}$$

$$\omega = \omega^* - mQ - m_d \frac{dQ}{dt} \tag{6}$$

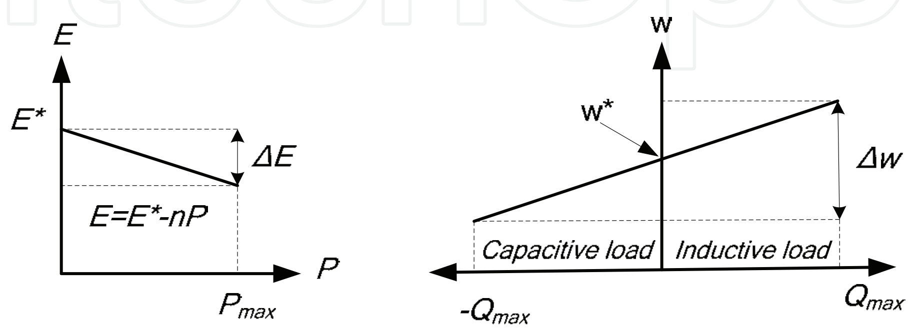

Fig. 12. Static droop/boost characteristics for resistive output impedance (Guerrero J.M, García de Vicuña et al. 2003; Guerrero, Vicuña et al. 2004; Guerrero, Berbel et al. 2006; Guerrero 2006; Guerrero 2005).

Where P is active power, Q is reactive power, E is output voltage, ω is angular frequency and m and n are the droop coefficients for the frequency and amplitude, respectively. As an addition in (Guerrero 2006) a soft-start is included to avoid the initial current peak as well as a bank of band pass filters in order to share the significant output-current harmonics. In more recent papers (Guerrero, Berbel et al. 2007; Josep M. Guerrero, Juan C. Vásquez et al. 2007) the authors use the conventional droop equations for a microgrid too.

$$E = E^* - n(Q - Q^*) \tag{7}$$

$$\omega = \omega^* - m(P - P^*) \tag{8}$$

c. Droop Control in Combination with Other Methods

In (Brabandere, Bolsens et al. 2004; K. De Brabandere, A. Woyte et al. 2004; De Brabandere, Vanthournout et al. 2007; Brabandere October, 2006) each inverter supplies a current that is the result of the voltage difference between a reference AC voltage source and the grid voltage across a virtual impedance with real and/or imaginary parts. This is shown in Fig. 13. The reference AC voltage source is synchronized with the grid, with a phase shift, depending on the difference between nominal and real grid frequency. This method behaviour is equal to the normal existing droop control methods except that, short-circuit behaviour is better since it is controlling the active and reactive currents and not the power. It behaves also better in case of a non-negligible line resistance.

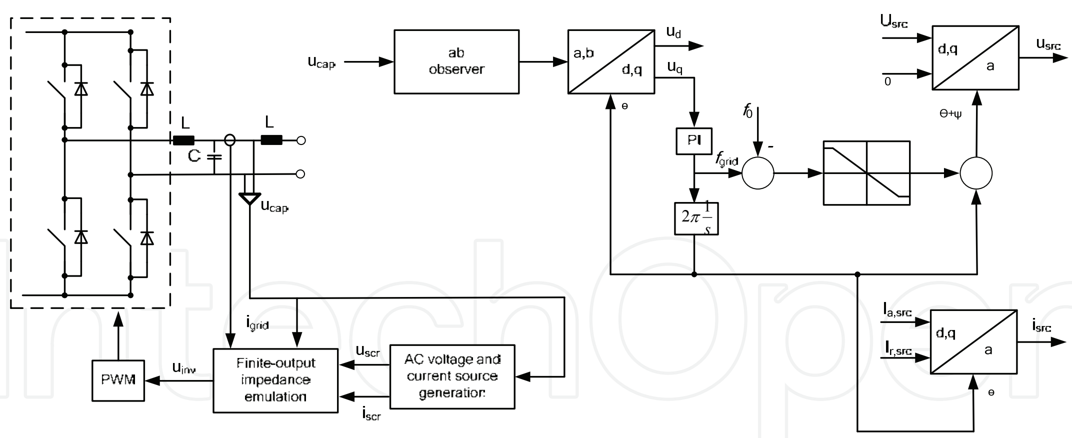

Fig. 13. Overall scheme for the proposed droop control method (Brabandere, Bolsens et al. 2004; K. De Brabandere, A. Woyte et al. 2004; De Brabandere, Vanthournout et al. 2007; Brabandere October, 2006).

In (E. Hoff 2004; T.Skjellnes, A.Skjellnes et al. 2002) novel fast control loops that adjust the output impedance of the closed-loop inverters is used in order to ensure resistive behaviour with the purpose to share the harmonic current content properly. In the measurements part a notch filter is added to remove the unwanted harmonics, it seems that without this filter the voltage regulator will not work efficiently. Furthermore, the control is done in the αβ-coordinates using a discrete controller.
The author of (Mihalache 2003) discusses the problem of inverters with very low output impedance (such as those employing resonant controllers) directly connected in parallel through a near zero impedance cable. Low total harmonic distortion (THD) content and good current sharing are simultaneously obtained by controlling the load angle through an least mean square estimator and by synthesizing a variable inductance in series with the output impedance of the inverter, while the harmonic current sharing is achieved by controlling the gain of the resonant controllers at the selected frequencies.

The authors of (Ernane Antonio Alves Coelho, Cortizo et al. 2000; Ernane Antonio Alves Coelho, Porfirio Cabaleiro Cortizo et al. 2002) introduced fast control loops that adjust the output impedance of the closed-loop inverters in order to ensure inductive behaviour with the purpose to share the harmonic current content properly. The paper presents a small-signal analysis for parallel-connected inverters in stand-alone AC power systems. The control approaches have an inherent trade-off between voltage regulation and power sharing (Guerrero, Berbel et al. 2006).
The signal injection technique proposed by (A. Tuladhar 1998; Tuladhar 2000) is not dependent in the plant parameters and can share reactive power even if the VSCs have not perfectly matched output inductors by having each VSC inject a non-60-Hz signal and use it as a means of sharing a common load with other VSCs on the network. However, the circuitry required to measure the small real power output variations due to the injected signal adds to the complexity of the control (C.K. Sao). Moreover, the controllers use an algorithm which is too complicated to calculate the current harmonic content, the harmonic current sharing is achieved at the expense of reducing the stability of the system (Guerrero J.M, García de Vicuña et al. 2003).

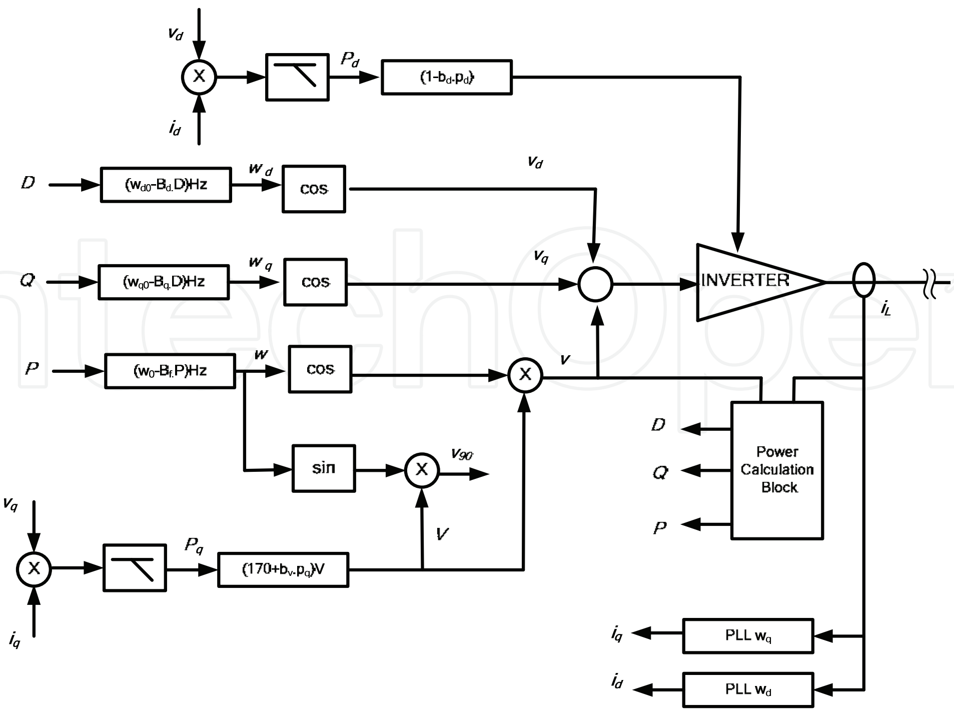

Fig. 14. Schematic diagram of implementing the signal injection technique (Tuladhar 2000).

In (Marwali, Jung et al. 2004) the proposed control method uses low-bandwidth data communication signals between each generation system in addition to the locally measurable feedback signals. The focus is on systems of distributed resources that can switch from grid connection to island operation without causing problems for critical loads. This is achieved by combining two control methods: droop control method and average power control method. In this method, the sharing of real and reactive powers between each DGS is implemented by two independent control variables: power angle and inverter output voltage amplitude. However, adding external communication can be considered as a drawback. Such communications increase the complexity and reduce the reliability, since the power balance and the system stability rely on these signals (Guerrero, Berbel et al. 2006). In (Glauser, Keller et al. 2000; Chen, Kang et al. 2004) a communication bus is used in addition to the conventional droop, it has to trigger all inverters to measure their load sharing parameters at the same line period, this is used to correct the load sharing calculation.

4.4 Discussion

The master/slave control configuration has many good characteristics. The inverters do not need a PLL circuit for synchronisation and give a good load sharing. The line impedance of the interconnecting lines does not affect the load sharing and the system is also easily expandable. There are, however, a few serious disadvantages. One of the major disadvantages is that most of these systems are not truly redundant, and have a single point of failure, the master unit. Another disadvantage of this configuration is that the stability of the system depends upon the number of slave units in the system (Tuladhar 2000). Furthermore, all these master/slave techniques, need communication and control interconnections, so they are less reliable for a distributed power supply system.

The current/power deviation (sharing) control techniques have excellent features. It has a very good load sharing, transient response and can reduce circulating currents between the inverters. There are as well some drawbacks. It is not easily expandable due to the need for measuring the load current and the need to know the number of inverters in the system. The needed interconnection makes the system less reliable and not truly redundant and distributed.
Droop control methods are based on local measurements of the network state variables which makes them truly distributed and give them an absolute redundancy as they do not depend on cables/communication for reliable operation. It has many desirable features such as expandability, modularity flexibility and redundancy. Nevertheless, the droop control concept has some limitations including frequency and amplitude deviations, slow transient response and possibility of circulating current among inverters due to wire impedance mismatches between inverter output and load bus and/or voltage/current sensor measurement error mismatches.
Each of these control techniques has its own characteristics, objectives, limits and appropriate uses. That often makes it difficult to adapt one control scheme for all applications. However, a deep understanding of these control techniques will help in enhancing them and though will improve the design and implementation of future distributed modular grid architectures.

5. The Proposed Smart Grid Philosophy

A general philosophy to supply electric energy in isolated power systems through power electronic inverters is introduced in (Omari 2005) and is extended here. The basic system philosophy is illustrated through Fig. 15. The power produced by the ECS is fed through the DC-to-DC converter and after that this DC power is fed to the grid through the inverter. The inverter produces an AC output of a specific voltage magnitude and frequency. The intermediate capacitance is used to decouple the DC current flowing to the input terminal of the grid-inverter from the DC current flowing from the DC-to-DC converters of the ECS side.

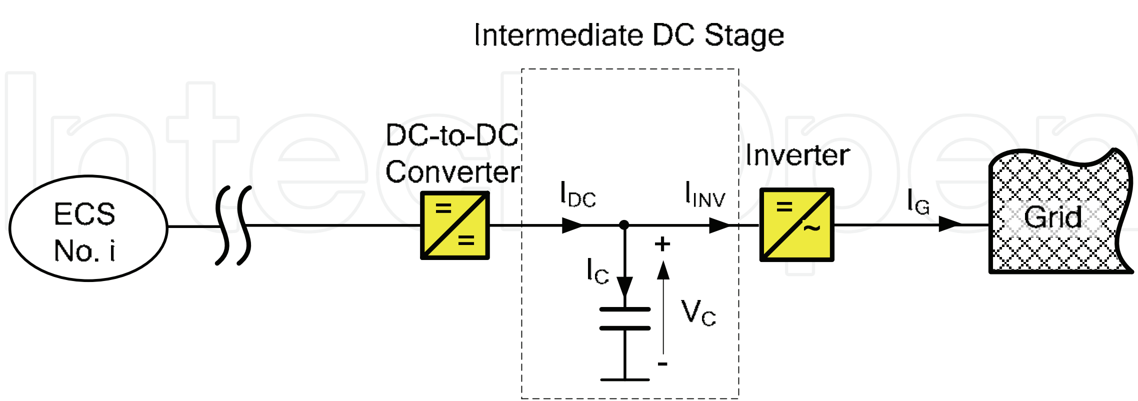

Fig. 15. System overview of the intermediate DC stage.

The mismatches between these two currents result in variations in the voltage across the intermediate capacitance caused by changes in the capacitor's current. This can be expressed using the following equation:

$$V_C = \frac{1}{C}\int I_C dt + V_{C,0} = \frac{1}{C}\int (I_{DC} - I_{INV})dt + V_{C,0} \tag{9}$$

Where the voltage across the intermediate capacitance is V_C, the output current of the DC/DC converter is I_{DC} and the input current to the inverter is I_{INV}.
These voltage variations can be utilised to control the power flow. The size of the capacitor is determined depending on the maximum possible mismatches between power production and power consumption. The voltage variations across the capacitor should be kept within the allowable ranges.
This intermediate DC stage has two important characteristics. First, it provides a decoupling between the voltages across the terminals of the ECSs from one side and the grid voltage from the other side. Second, it provides a decoupling between the frequency of the ECSs (in the case of AC energy conversion systems) from one side and the grid frequency from the other side. In this philosophy the power flow from an energy conversion source (ECS) into the grid may be driven by the grid or by the ECS itself as summarised in Fig. 16.

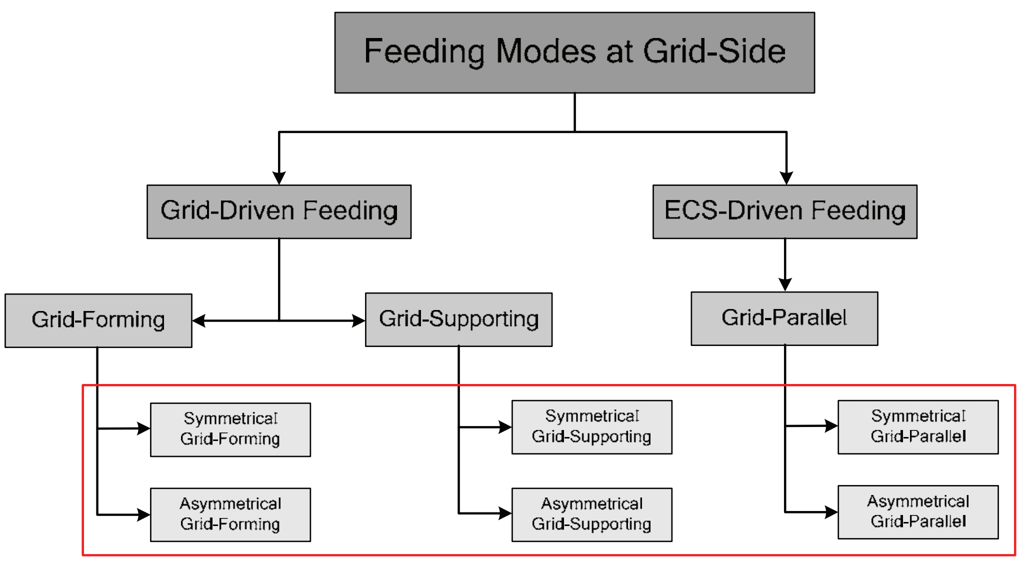

Fig. 16. A general definition of feeding modes for DER.

In a grid-driven feeding mode the flow of power from the ECS to the grid is controlled according to the requirements of the grid while in an ECS-driven feeding mode, the flow of power is controlled according to the requirements of the ECS itself. In the second case, ECSs are normally controlled to maximise their power production despite the requirements of the grid. The grid-driven feeding mode represents the active integration case while the ECSs-driven feeding mode represents the passive one. A grid-driven feeding mode may be realised through two different cases: grid-forming case and grid-supporting case, while an ECS-driven feeding mode may be realised through a grid-parallel case.
An ECS in a grid-forming case is responsible for establishing the voltage and the frequency of the grid (state variables) and maintaining them (Omari 2005). This is done by increasing or decreasing its power production in order to keep the power balance in the electrical system.
An ECS in a grid-supporting case produces predefined amounts of power which are normally specified by a management unit. Therefore, the power production in such a case is

not a function of the power imbalances in the grid. Nevertheless, the predefined amounts of power for these units may be adjusted. The management system may change the reference values according to the system's requirements and the units' own qualifications. The control strategy of the intermediate DC circuit is derived from the feeding modes definition. Therefore, in the grid-driven feeding mode the voltage across the capacitor is kept within the allowable ranges through controlling I_{DC} current while keeping I_{INV} free to change, see Fig. 17.

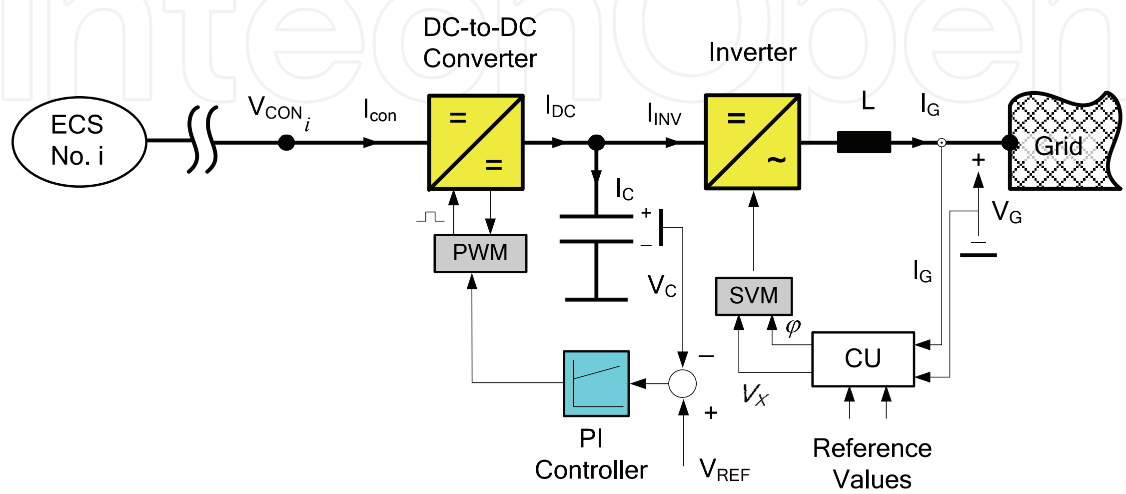

Fig. 17. General control of a system operating in a grid-driven feeding mode (Forming, Supporting).

An ECS in a grid-parallel case is a power production unit that is not controlled according to the requirements of the electrical system. RES's such as wind energy converters and photovoltaic systems may be used to feed their maximum power into the grid (standard applications in conventional grids). In such a case, these systems are considered as grid parallel units. For the ECSs-driven feeding mode control strategy the vice versa applies, I_{INV} is controlled and I_{DC} is free to change, see Fig. 18.

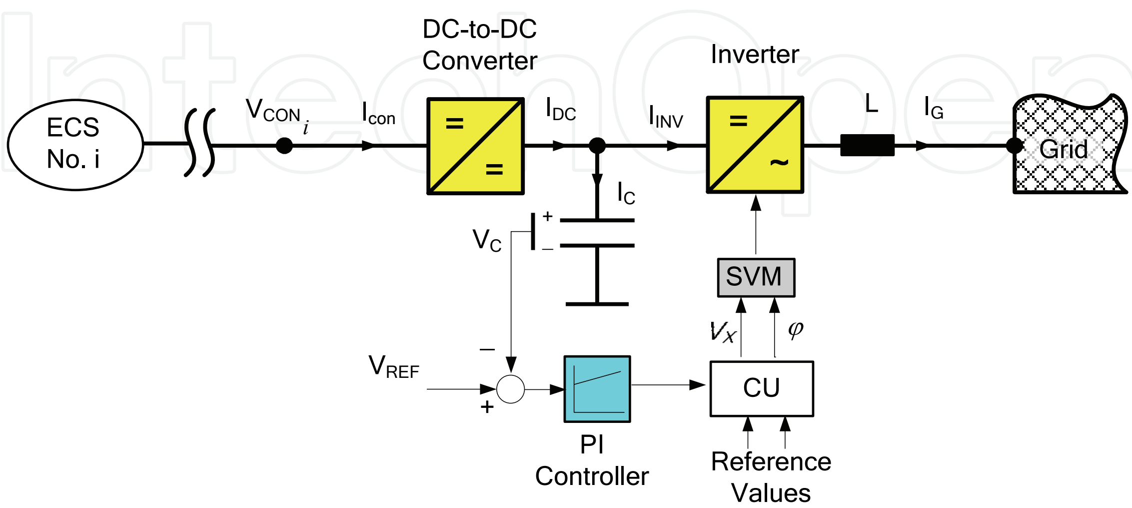

Fig. 18. General control of a system operating in ECSs-driven feeding mode (parallel).

5.1 Inverter Topologies

To articulate the control strategies in relation to power electronic devices a short introduction of the different used three-phase inverter topologies is given.

a) Three-phase, Three-leg Voltage Source Inverters

Three single-phase half-bridge inverters can be connected in parallel to form the three phase inverter configuration, one leg for each phase, see Fig. 19. The gating signals of single-phase inverters should be advanced or delayed by 120 degree with respect to each other in order to obtain three-phase balanced voltages (Rashid 1995). In this case it requires that the three currents are a balanced three-phase set. However, this topology can be used to feed balanced loads only.

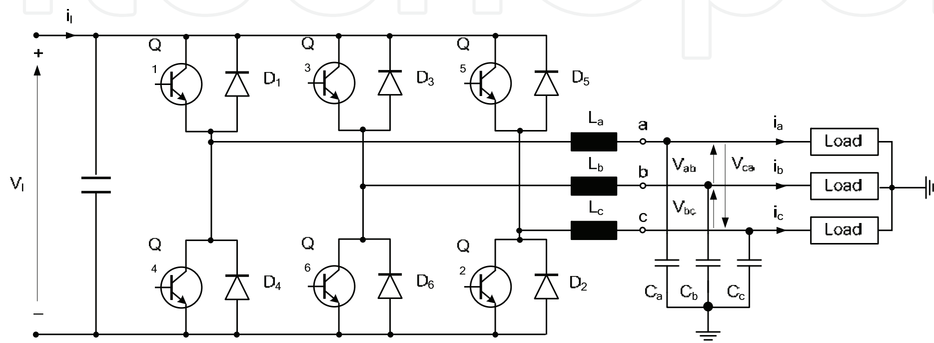

Fig. 19. Three leg inverter (balanced output).

Two configurations able to generate three-phase asymmetrical signals will be discussed. These are: The three-leg neutral point built by capacitors and the four-leg inverter with a controlled neutral point by the fourth leg.

b) Three-phase, Three-leg, Four-wire Voltage Source Inverters

Three-phase inverters with neutral point are an evolution from the single-phase ones. Three half-bridge single-phase inverters joined together can be seen as a three-phase neutral point inverter, see Fig. 20, where each output feeds one phase. This topology can be used to feed balanced or unbalanced loads. In case of unbalanced loads, the sum of the output currents i_a, i_b, and i_c will not be zero and the neutral current will flow in the connection between the neutral point and the mid-point of the capacitive divider (G. Seguier and Labrique 1993; Said El-Barbari and Hofmann 2000; Omari 2005). To maintain a symmetrical voltage across the two capacitors an adequate power electronic and a voltage stage management are needed, this will not be taken further into discussion.

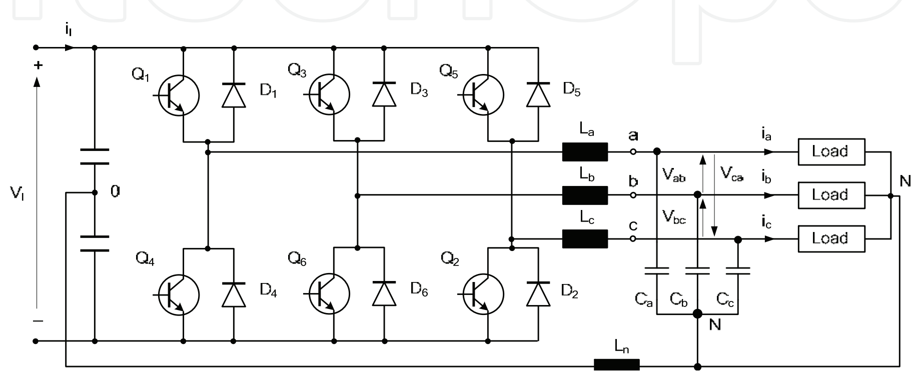

Fig. 20. Three-leg inverter with a neutral point.

c) Three-phase, Four-leg Voltage Source Inverters

The general power electronic topology of the four-legged inverter is shown in Fig. 21. The goal of the three-phase four-leg inverter is to supply a desired sinusoidal output voltage waveform to the load for all load conditions and transients. By tying the load neutral point to the mid-point of the fourth leg, it can handle the neutral current caused by an unbalanced load. A balanced output voltage can be achieved due to the tightly regulated neutral point. The additional neutral inductor L_n is optional. It can reduce switching frequency ripple (Zhang 1998). A four leg inverter can produce sixteen switching states. This enlarges the space vector modulation to three-dimensional (3-D-SVM), for a four-leg voltage source inverter the representation of the phase voltage space vectors is done in the α,β,γ space.

Compared with the four-leg inverter, the three-leg four-wire inverter has a lower number of semiconductor switches and the control function can be built like three individual single line inverters. However, the four-leg inverter still has the advantages of higher utilization of the DC link voltage. This is because the maximum available peak value of the line-to-neutral output voltage in the three-leg four-wire inverter is equal to half the value of the dc link voltage while the maximum amplitude of the line-to-line voltage with a four-leg inverter is equal to the dc bus voltage. Moreover, the high unbalanced current flowing through the dc link capacitors of the three-leg four-wire inverter requires higher capacitance (Zhang, Boroyevich et al. 1997; Maria Brucoli and Green 2006). So, the four-leg inverter has small DC link capacitor as no zero sequence current flow across the DC link capacitor and has an additional degree of freedom due to the fourth leg (Said El-Barbari and Hofmann 2000; E. Ortjohann 2006; E.Ortjohann, A.Mohd et al. 2006).

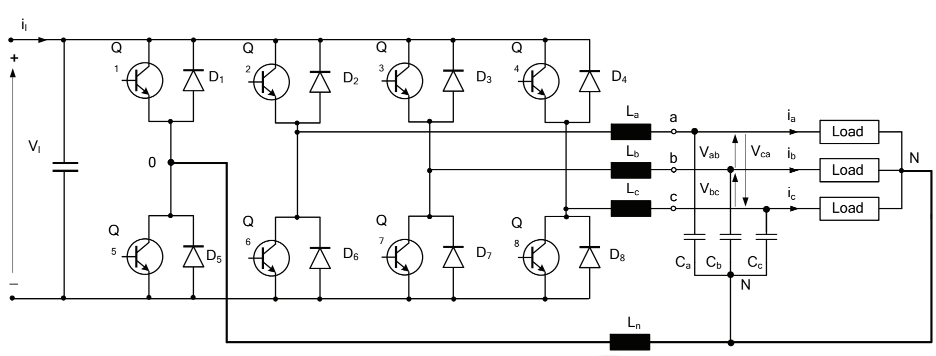

Fig. 21. Four-leg inverter.

In general, three-leg inverter will use the two-dimensional space vector modulation (2-D-SVM). On the other hand, the three-leg inverter with neutral point and the four leg inverter will extend the space vector modulation to three-dimensional (3-D-SVM) making the selection of the modulation vectors more complex. The 3-D-SVM of three-leg with neutral point inverter differ from that of the four leg inverter. Nevertheless, the control strategies are similar. Both the control strategies and the SVM algorithms will be discussed in detail in the following sections.

5.2 Inverter Control

In the following sections, the known control strategies of symmetrical inverters will be briefly reviewed; Further details can be found in (Omari 2005). Afterwards, the proposed control strategies for the asymmetrical inverters will be introduced, these were published in papers (Egon Ortjohann, Mohd et al. 2006; E.Ortjohann, A.Mohd et al. 2006).

5.2.1 Symmetrical Grid Forming

The control strategy of a three-phase inverter in grid forming mode for balanced load is shown in Fig. 22. The inverter in this case determines the voltage and the frequency of the grid. There is one inner current control loop and a second voltage control loop. Both loops use only the d-component. The q-component of the current cannot be influenced since the reactive part is depending on the load condition. Therefore, the q-component is not considered in this case. The reference angle for the dq-transformation is taken from the reference frequency.

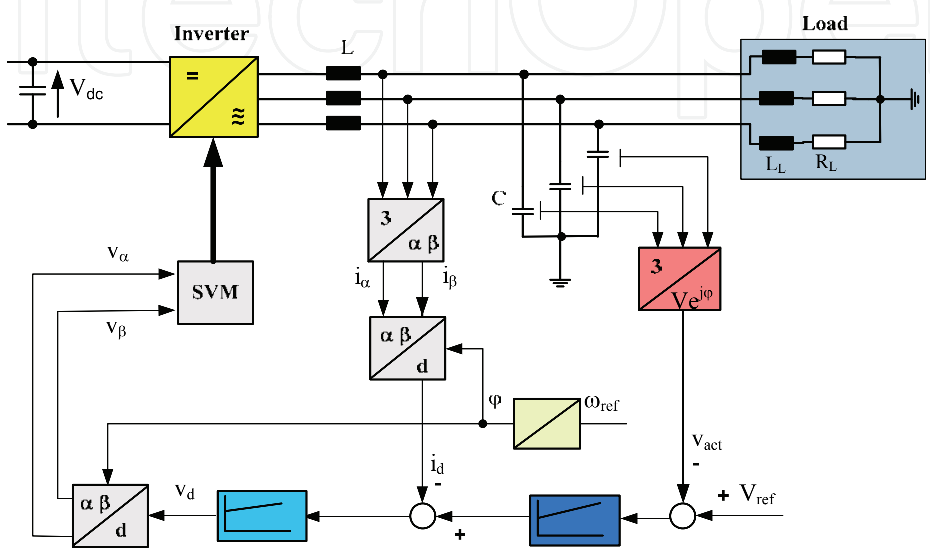

Fig. 22. Inverter in grid forming mode for balanced loads.

5.2.2 Symmetrical Grid Supporting

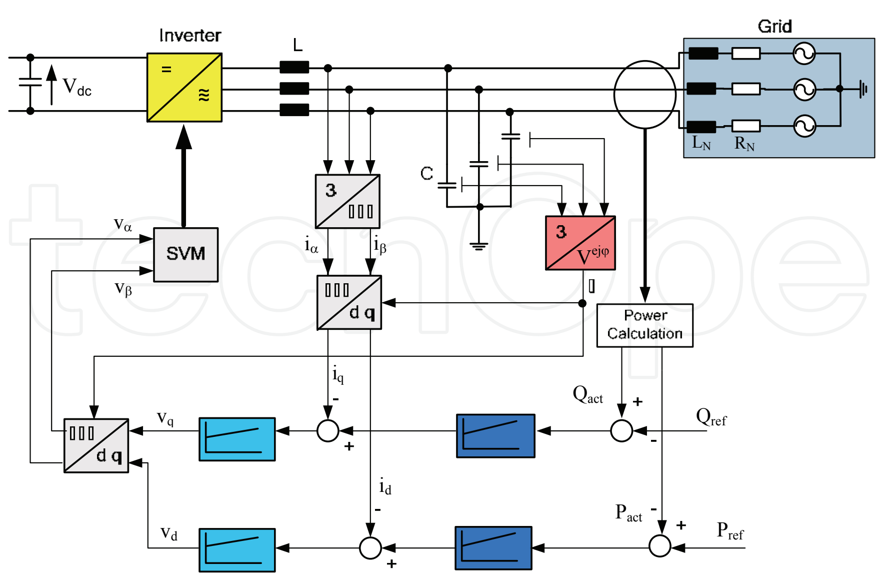

Fig. 23. P, Q-controlled inverter in grid supporting mode for balanced loads.

The grid supporting unit for balanced loads feeds the grid with a specified amount of power, which might be active, reactive, or a combination of both, see Fig. 23. The control strategy for the grid supporting unit using active and reactive power has four controllers, two for the current (i_d and i_q), and two for the power (P and Q). Active power, *P*, is controlled by the real part of the grid current "i_d", while reactive power, *Q*, is controlled by the imaginary part "i_q". Synchronization is implemented by the generation of the angle for the dq transformation from the voltage on the grid. Other control strategies for the grid supporting mode can be implemented straight forward through controlling the real and the imaginary components of the grid current or the magnitude of the voltage and the active component of the power fed into the grid.

5.2.3 Symmetrical Grid Parallel

In the case of grid-parallel feeding mode, see Fig. 24, all of the produced active power by the ECS is passed to the grid through the inverter. The active power management is done in this application by the control of the voltage of the DC stage. The reactive power control is similar to the grid supporting case.

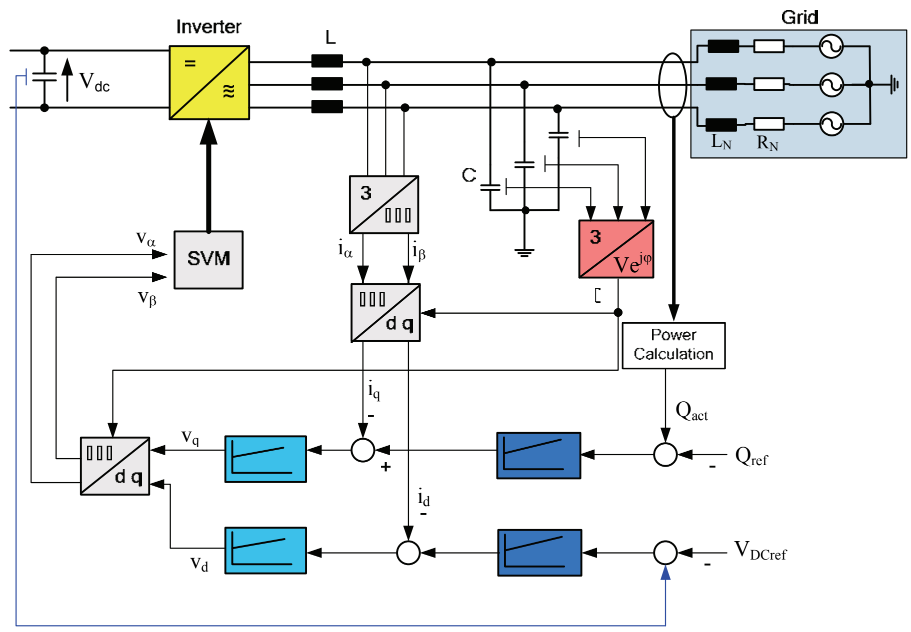

Fig. 24. Q-controlled inverter in grid parallel mode.

5.2.4 Asymmetrical Grid Forming

As a grid forming unit the inverter has to provide both the voltage and the frequency of the grid. This is done as following: The voltage and the current sensed values are transformed from the abc-frame to the positive-negative-zero dq sequence components. The controller block comprises current and voltage PI controllers for each component. Six controllers are needed for the voltage and the current components of the load. For the controller only the *d*-component of the positive sequence $V_{p\_d\_ref}$ is considered. The other reference values are set to zero since the inverter has to supply symmetrical three phase voltage. The output reference values from the control unit are transformed to the αβγ-space and the SVM block uses them to calculate the pulse pattern for the switches (Egon Ortjohann, Mohd et al. 2006). Fig. 25 shows an inverter in grid forming mode for unbalanced loads. The control functions can be also described as vectors according to the following definition:

$$[V_{pn0\_dq\_ref}] = \begin{bmatrix} V_{p\_d\_ref} \\ V_{p\_q\_ref} \\ V_{n\_d\_ref} \\ V_{n\_q\_ref} \\ V_{0\_d\_ref} \\ V_{0\_q\_ref} \end{bmatrix} \qquad [V_{pn0\_dq\_act}] = \begin{bmatrix} V_{p\_d\_act} \\ V_{p\_q\_act} \\ V_{n\_d\_act} \\ V_{n\_q\_act} \\ V_{0\_d\_act} \\ V_{0\_q\_act} \end{bmatrix} \tag{10}$$

$$[V_{pn0\_dq}] = \begin{bmatrix} V_{p\_d} \\ V_{p\_q} \\ V_{n\_d} \\ V_{n\_q} \\ V_{0\_d} \\ V_{0\_q} \end{bmatrix} \qquad [I_{pn0\_dq\_act}] = \begin{bmatrix} I_{p\_d\_act} \\ I_{p\_q\_act} \\ I_{n\_d\_act} \\ I_{n\_q\_act} \\ I_{0\_d\_act} \\ I_{0\_q\_act} \end{bmatrix} \tag{11}$$

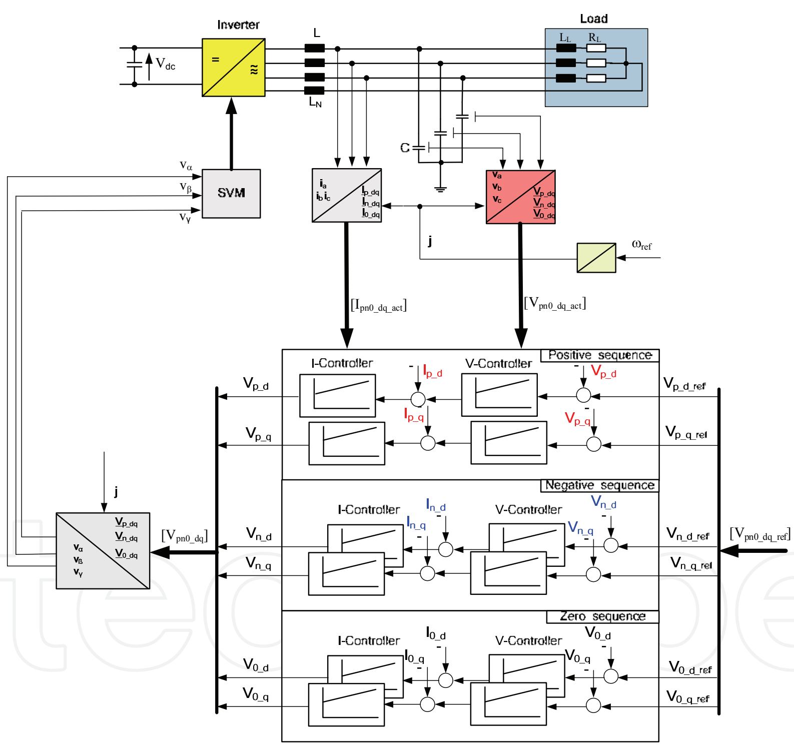

Fig. 25. Inverter in grid forming mode for unbalanced loads.

5.2.5 Asymmetrical Grid Supporting

The asymmetrical grid supporting unit has to supply the grid with a specified amount of power, which might be active, reactive, or a combination of both as mentioned before. Synchronisation with the grid voltage is done by the voltage reference angle which has to be generated as in the symmetrical grid supporting mode. The desired amount of power has to be set by a management unit in positive, negative and zero sequence components. The power controller block generates a reference signal for the current controller. The current controller is delivering a reference voltage signal represented by positive, negative and zero sequence components. These reference values have to be transformed (composed) to the αβγ-space vector and the SVM block uses them to calculate the pulse pattern for the switches (Egon Ortjohann, Mohd et al. 2006). Fig. 26 shows a *P*, *Q*-controlled Inverter in grid supporting mode for unbalanced loads, the control functions can be also described as vectors according to the following definition:

$$[P_{pn0\_ref}] = \begin{bmatrix} P_{p\_ref} \\ P_{n\_ref} \\ P_{0\_ref} \end{bmatrix} \qquad [Q_{pn0\_ref}] = \begin{bmatrix} Q_{p\_ref} \\ Q_{n\_ref} \\ Q_{0\_ref} \end{bmatrix} \tag{12}$$

$$[P_{pn0\_act}] = \begin{bmatrix} P_{p\_act} \\ P_{n\_act} \\ P_{0\_act} \end{bmatrix} \qquad [Q_{pn0\_act}] = \begin{bmatrix} Q_{p\_act} \\ Q_{n\_act} \\ Q_{0\_act} \end{bmatrix} \tag{13}$$

$$[I_{pn0\_d\_act}] = \begin{bmatrix} I_{p\_d\_act} \\ I_{n\_d\_act} \\ I_{0\_d\_act} \end{bmatrix} \qquad [I_{pn0\_q\_act}] = \begin{bmatrix} I_{p\_q\_act} \\ I_{n\_q\_act} \\ I_{0\_q\_act} \end{bmatrix} \tag{14}$$

$$[V_{pn0\_d}] = \begin{bmatrix} V_{p\_d} \\ V_{n\_d} \\ V_{0\_d} \end{bmatrix} \qquad [V_{pn0\_q}] = \begin{bmatrix} V_{p\_q} \\ V_{n\_q} \\ V_{0\_q} \end{bmatrix} \tag{15}$$

Other control strategies can be implemented simply through the real and the imaginary components of the grid current or the magnitude of the voltage and the active component of the power fed into the grid.

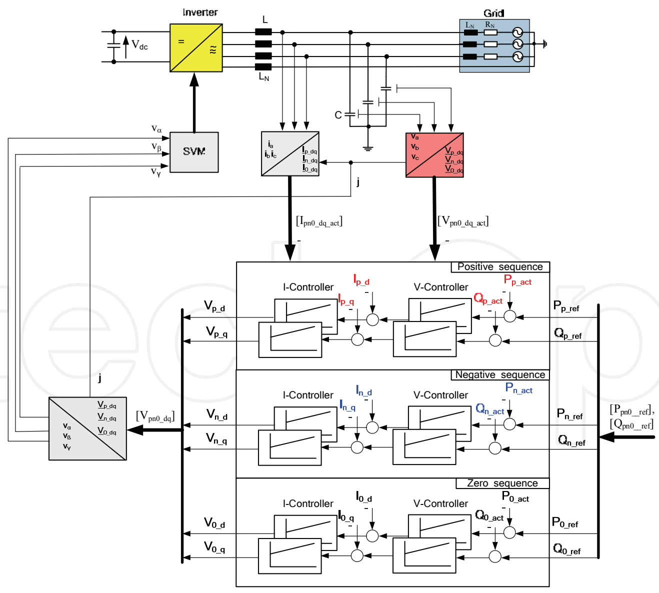

Fig. 26. P, Q-controlled Inverter in grid supporting mode for unbalanced loads.

5.2.6 Asymmetrical Grid Parallel

Obviously, in the case of asymmetrical grid-parallel unit, shown in Fig. 27, the values that can be controlled are the flow of the reactive power or reactive current to the grid. In comparison to the asymmetrical grid supporting remarkable is the active power control using V_{dc} and:

$$[P_{n0\_ref}] = \begin{bmatrix} P_{n\_ref} \\ P_{0\_ref} \end{bmatrix} \qquad [P_{n0\_act}] = \begin{bmatrix} P_{n\_act} \\ P_{0\_act} \end{bmatrix} \tag{16}$$

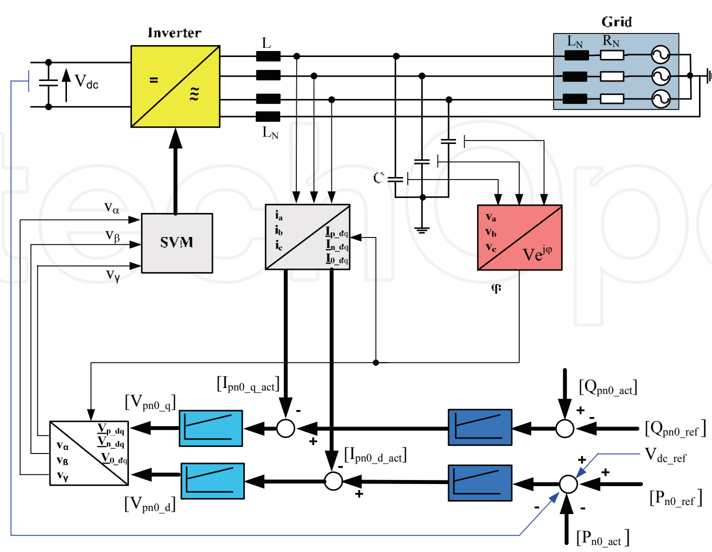

Fig. 27. Inverter in grid parallel mode for unbalanced loads.

This section presented the system components developed for the smart grid. Including the general feeding architecture was presented and discussed. Then it presents the main power electronic element of the philosophy, the inverter, showing the different topologies used. Finally, the operating principles and control techniques for these inverters were presented. This included novel standardized advanced control concept for four-wire inverters (three-leg four-wire and four-leg) using symmetrical components based on sequence decomposition to supply balanced/unbalanced loads. The principle idea is to control the positive, negative and zero sequence components. Controlling (eliminating) the negative and zero sequence components helps expanding the inverter based systems by increasing the distribution network efficiency (consequently leads to less losses and results in enhancing the power quality). This can be used for shunt active filters' applications and also grant the opportunity to supply unbalanced loads which mean supplying single and three phase loads using the same source.

6. The Proposed Smart Grid philosophy "Operation, control, and management"

In the previous section, the principles of the proposed smart grid philosophy and its components have been introduced. In this chapter, the operation, control, application and management of this philosophy are going to be presented.

Even though, most of the current approaches to build future smart power systems are trying to introduce one-size-fits-all solution but the fact is that each system (customer) needs are different and various approaches are needed to fit their exact specifications. This chapter will introduce varied opportunities of control functions for three-phase inverters used to feed passive/active grids including different topologies to feed balanced/unbalanced loads.

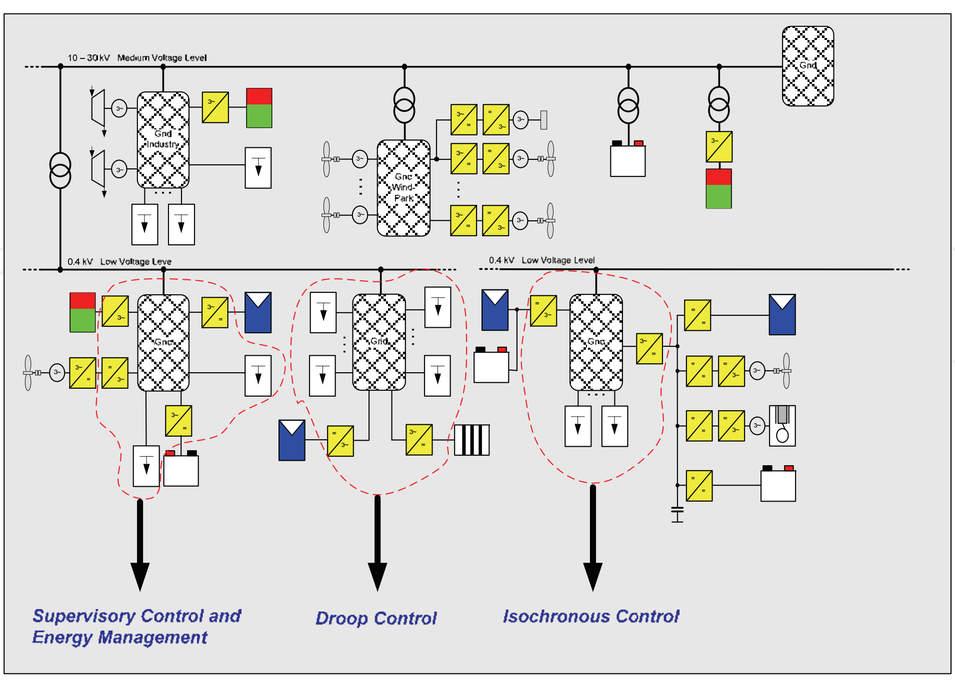

Fig. 28. The control philosophy (example).

The proposed philosophy will develop different and various robust control approaches for a realistic distributed power system with power electronics inverters as front-end, see Fig. 28. These control strategies should guarantee real modularity, higher reliability and avoid a single point of failure to qualify to be standardised. The proposed control architecture should maintain three phase voltages and frequency in the grid within certain defined limits and has to provide power sharing between the units according to their ratings and user settings.

The electrical energy produced by ECSs may be fed into the electrical grid according to one of two possible feeding modes. In the first mode, the amount of electrical energy fed into the grid is specified according to the grid requirements. This mode is denoted as a "Grid-driven feeding mode". In the second mode, the ECSs specify the amount of energy fed into the grid. This mode is denoted as an "ECSs-driven feeding mode". Fig. 29 presents a diagram showing the structure of the control functions proposed in this research study. These control strategies will be launched in this chapter.

The system philosophy under discussion is also characterised by an intermediate DC stage between the energy sources from one side and the electrical grid from the other side. From the DC-DC converters' side, it connects to the ECSs and from the main inverter's side it connects to the electrical grid, see chapter three. However, in order to simplify the analysis, the ECSs-side (the generation sources such as PV and fuel cells) are represented using a DC voltage source.

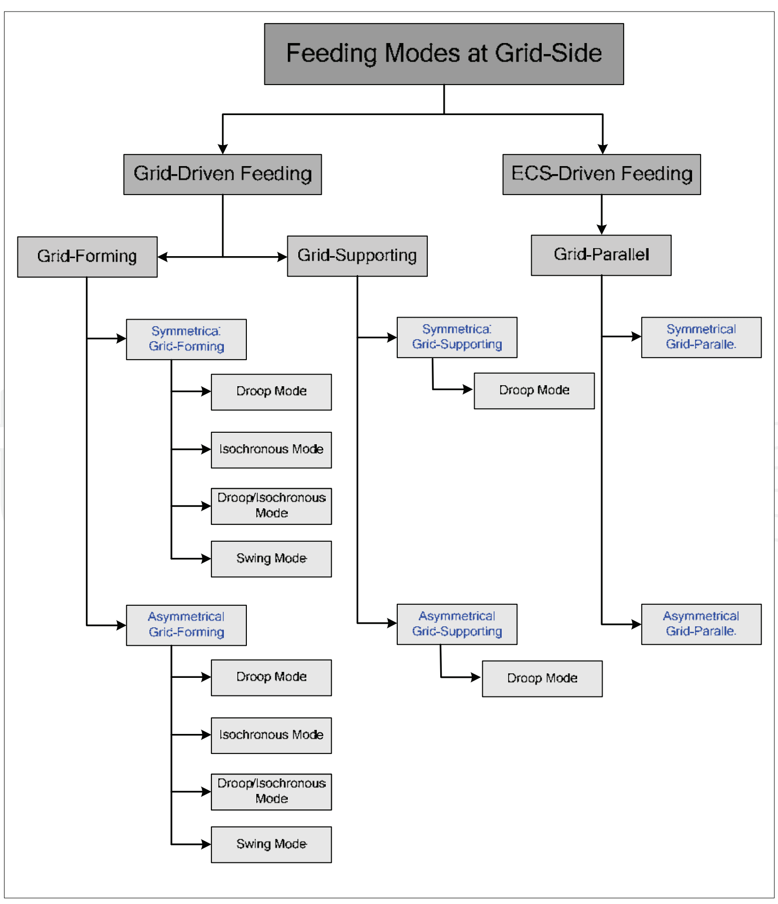

Fig. 29. Feeding modes at the grid side.

Based on the modes proposed in Fig. 29. many scenarios can be obtained. The key scenarios are taken into account in this research study as shown in Fig. 30. The proposed philosophy has two main categories. The first category is the Multi-inverter Three-wire system and the second is the Multi-inverter Four-wire system. For each of these categories different control scenarios will be proposed and explored.

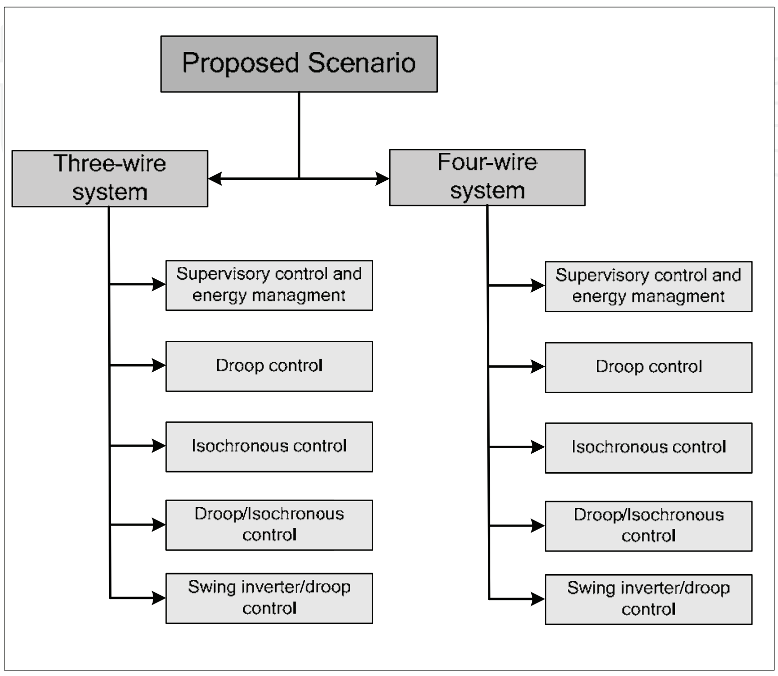

Fig. 30. The proposed scenarios.

6.1 Multi-inverter Three-wire System Control Philosophy

Since the inverters are relatively stiff sources, with unique value of open circuit frequency and voltage (due to components tolerance), large circulating currents would result if they were simply paralleled without additional control. This can be done based on information available locally at the inverter (state variables) for example using droops to make the system less stiff or using data communication such as in supervisory controlled systems. Recently data communication between units became easy realized by the rapid advances in the field of communication. However, it is preferred that communication of information will be used to enhance system performance but must not be critical for system operation. The following sections will introduce modular approaches to parallel inverters using different methodologies.

6.1.1 Supervisory Control and Energy Management Scenario

The specific aim of this concept is to develop a standardised control strategy for a realistic distributed power system with power electronics inverters as front-end. The proposed control architecture will maintain the three phase voltages and frequencies in the grid precisely and will provide power sharing between the units according to their ratings, meteorological parameters, economical dispatch prospective (can include real-time pricing) and user settings. This allows total energy optimization. The designed system can include inverter units of different power rating, distributed at various locations feeding distributed unequal loads taking into account dissimilar line impedances between them to insure true expandability and generation placement flexibility. This means that the types, sizes, and numbers of the inverters, and the size and nature of the electrical loads may all vary without the need to alter the control strategy. The amount of data exchange can be small if it includes only basic measurements and set points but will increase proportionally as more functions are added. The proposed structure is shown in Fig. 31. It is worthy to note that the source do not have to be a single ECS and could be a hybrid power system (HPS).

The supervisory control is responsible for units dispatching, load management, and power optimization. It can include also many functions like meteorological forecasting and demand side management as illustrated in (Osama Omari, Egon Ortjohann et al. 2007). It can also manage an intelligent switch or a feeder to the main grid or to other mini-grids. The current and voltage control are done locally at the inverters according to the definition introduced in chapter three. Moreover, the proposed control can be implemented not only in distribution system of isolated grid systems, but also in the interconnected power systems (some times called on-grid micro-grid).

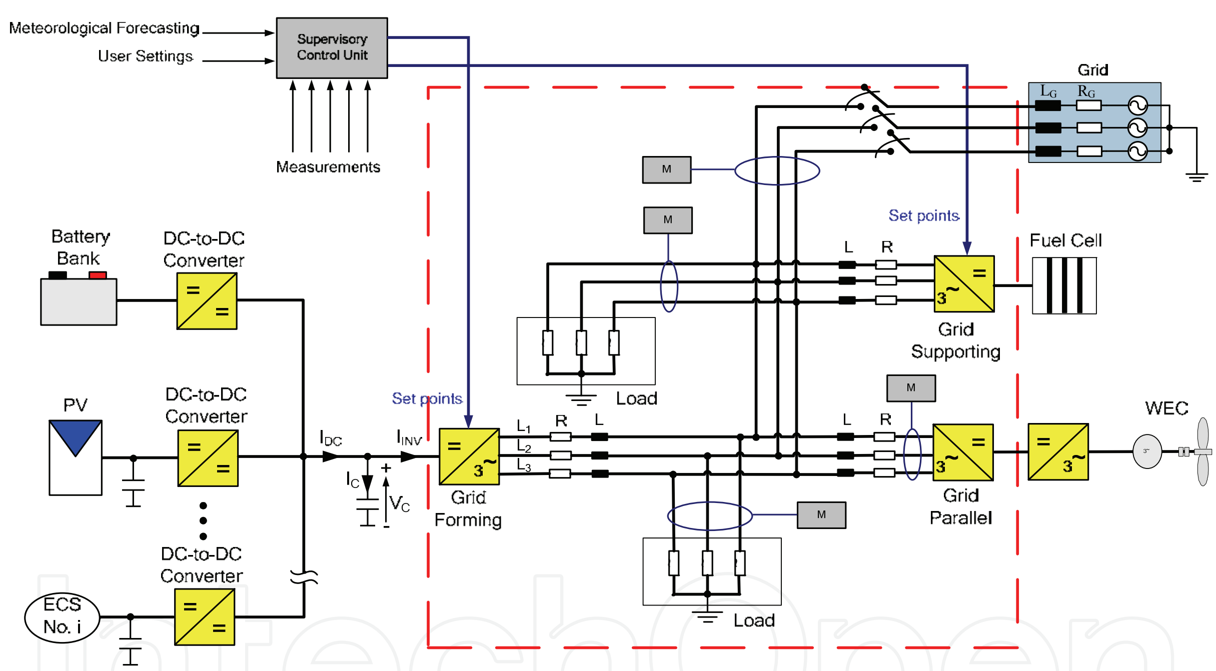

Fig. 31. Overview of supervisory control and energy management proposed system structure.

The control functions of the inverters are shown in Fig. 32 As mentioned in section 5, each grid mode has its own character for controlling the inverter. The grid forming contains inner current control loop and outer voltage control loop. The reference voltage is given to control the voltage of the system. The angular speed related to the frequency of the system is also set as constant (2πf). The control loop produce the voltage of d-axis which will be transformed to αβ frame, the angle is required for that. These voltages in αβ frame are supplied to the SVM to calculate the switching sequence and periods. In the next step the inverter supplies the three-phase currents to the system through the LC filter. The output currents will be measured to feed the signal to the inner current loop. The voltages across the capacitor are also measured to feed the outer control loop.

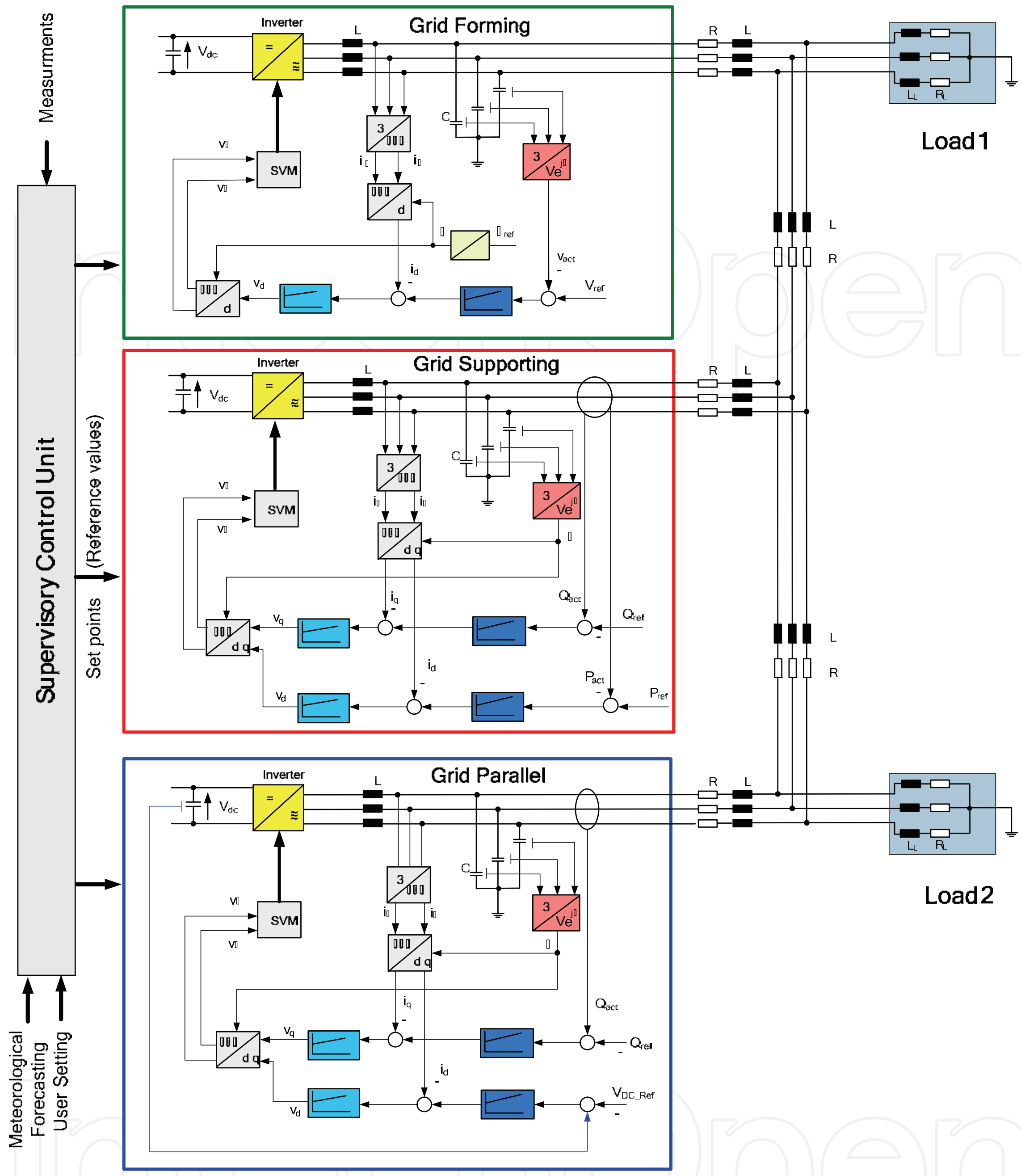

Fig. 32. Supervisory control and energy management scenario.

As stated previously, the responsibility of the grid supporting mode is to maintain the system power balance. The reference power of the grid supporting inverter is calculated in the supervisory unit based on other inverters in the system (grid forming and parallel modes) and loads. Moreover, it depends also on the pre-setting percentages or algorithms used in the supervisory control to manage the power balance. The reference values of P_{GS} and Q_{GS} are calculated based on that. In the simplest case, the set values can be adjusted by the percentage value ($GS_{percent}$) and the active power load (P_{load}) and reactive power load (Q_{load}). As a simple example, the set values of active and reactive power can be calculated via equations 17 and 18 respectively:

$$P_{GS\_ref} = \frac{\left(\sum_{i=1}^{n} P_{load_i} - \sum_{j=1}^{m} P_{GP_j}\right) \times GS_{percent}}{100} \tag{17}$$

$$Q_{GS\_ref} = \frac{\left(\sum_{i=1}^{n} Q_{load_i} - \sum_{j=1}^{m} Q_{GP_j}\right) \times GS_{percent}}{100} \tag{18}$$

Where, $\sum_{i=1}^{n} P_{load_i}$ and $\sum_{i=1}^{n} Q_{load_i}$ are the summation of the active and reactive power of load in the system, where, n is the number of loads and i is the counter. $\sum_{j=1}^{m} P_{GP_j}$ and $\sum_{j=1}^{m} Q_{GP_j}$ are the summation of the active and reactive power of grid parallel units in the system, where, m is the number of grid parallel units and j is the counter.
This means that the amount of power needed is deducted from the power of the grid parallel units since they cannot be influenced by the grid, the rest is shared between the grid forming and supporting according to the percentage $GS_{percent}$. This percentage can be calculated according to an algorithm based on the units' ratings, meteorological parameters, economical dispatch prospective and user settings but this will not be taken into discussion over here since its out of the scope of this study. This was demonstrated in (Osama Omari, Egon Ortjohann et al. 2007).

After the actual active and reactive power of the grid supporting mode is passed to the outer loop of the controllers, another inner current control loop is used. The current of d-axis is used to control the active power signal and the current of q-axis is used to control the reactive power signal.

The grid parallel mode is used to produce maximum amount of active power and can sometimes supply certain amount of reactive power to the system. In the voltage control loop, there are two reference inputs, voltage reference and reactive power reference. There are three inputs measured to calculate the new reference for I_d and I_q controllers. These are first, the DC intermediate stage which will be passed through the voltage controller to feed into the inner current loop for I_d controller; based on that the new reference of the voltage is established. The second input, is the three-phase voltage measured from the line. The three-phase voltage is transformed into dq-frame and the angle of the voltage can be measured from voltage of q-axis (V_q). The voltage magnitude is fed to the I_q controller which is compared to the reactive set value to get the new reference value for I_q controller. Third, the actual output current values measured are used by I_d and I_q controllers of the inner control loop. The current signals are transformed into dq-frame. After the controlled signals passed through the I_d and I_q controllers, both signals are added with the actual values of the voltage in dq-frame and then transformed into $\alpha\beta$ frame to control the inverter's output.

It should be also noticed that as a grid parallel unit, if the system frequency is rising too high the inverter's output should be reduced or set to zero (disconnected).

The following simulation case study is carried using MATLAB/Simulink to validate the proposed inverter supervisory control approach. The supervisory control is responsible for units dispatching, load management, and power optimization. However, the current and voltage control are done locally at the inverters according to the definition introduced before. The proposed control can be implemented in isolated grid as well as in interconnected power systems. In this case study there are three inverters operating in grid forming mode, grid supporting mode and grid parallel mode respectively. They are connected in parallel to supply two loads including steps as shown in Fig. 33.

The first load step is at t=1 second and the second load step is at t=1.5 second. At t=2 seconds, the active power of the grid parallel unit is stepped up from 14 kW to 21 kW. The frequency response of the system is shown in Fig. 34. At t=1 second, when the load is increased the frequency will drop. In the other hand at t=1.5 second, the load is decreased and then the frequency will rise. At t=2 second, the grid parallel gives more power to the system. As a response and to keep the frequency constant, the grid forming and supporting inverters will supply less power to the system.

Fig. 35 shows the active power response of the inverters and loads from 0.5 second to 2.5 seconds. At the first step (t=1 second), active power of load one is increased as shown in Fig. 35. Consequently, the active power of grid forming and grid supporting inverters are increased to balance with the increased load. The grid supporting takes 30 percent of the load as pre-set (This is the result based on the optimization algorithm). The active power of the grid parallel unit supplied to the system is the same. At second step (t=1.5 second), the active power of load two is decreased. The active power of the grid forming and grid supporting inverters are decreased, while the active power of the grid parallel inverter is still the same. At last step (2 second), the grid parallel is set to give more active power to the system.

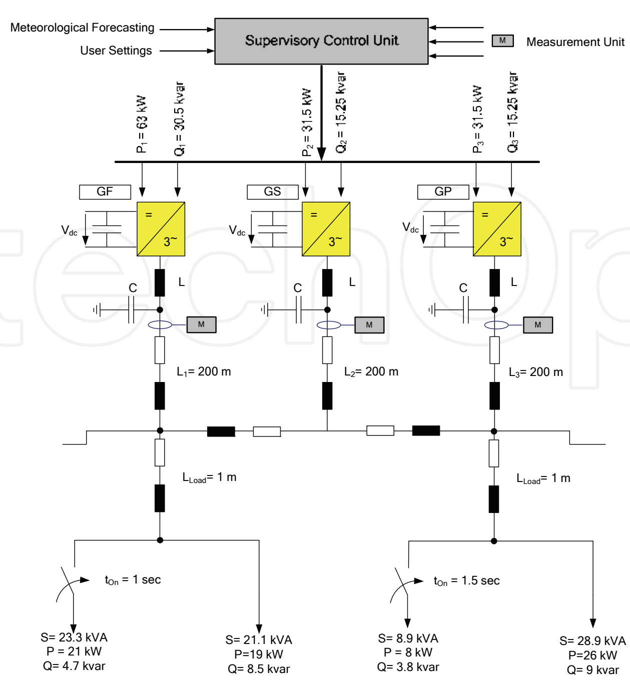

Fig. 33. Case Study.

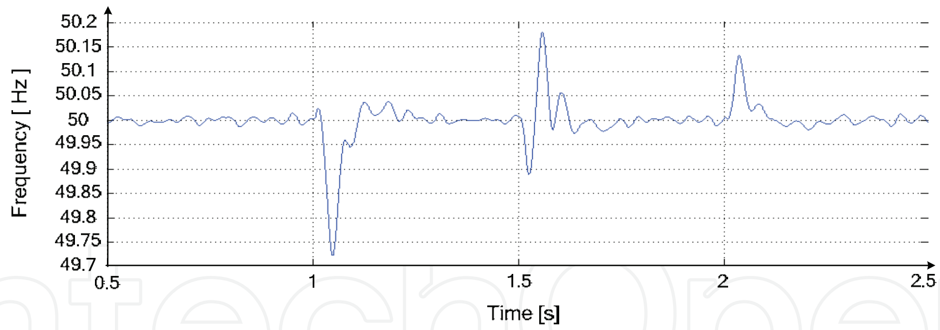

Fig. 34. The system frequency.

Therefore, the active power of the grid parallel inverter will increase and as a response both active power of grid forming and grid supporting inverters will be signaled to decrease since the load is kept constant. The exact values are shown in Table II and confirm the system active power balance.
The reactive power behavior of the inverters is similar to the active power. The difference is that the grid parallel inverter is set only to give more active power to the system and is not contributing to the reactive power balance. Therefore, it is not affecting the reactive power of the grid parallel unit at the last step as shown in Fig. 36; loads are almost the same. The exact values are shown in Table 2 and confirm the system reactive power balance.

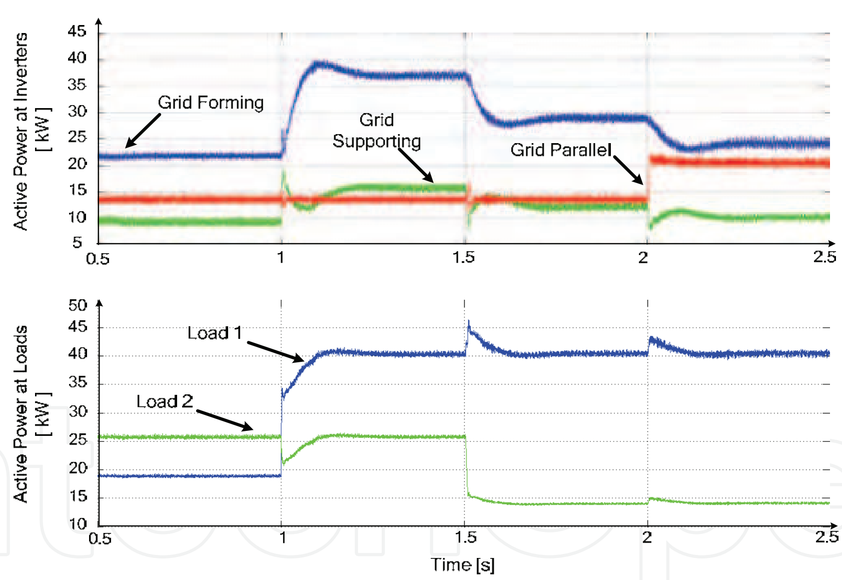

Fig. 35. The active power.

Time (s)	$P_{load\ 1}$	$P_{load\ 2}$	ΣP_{load}	*GF*	*GS*	*GP*
0 – 1.0	19	26	45	21.7	*9.3*	*14*
1.0 – 1.5	40	26	66	36.8	*15.6*	*14*
1.5 – 2.0	40	14	54	28	*12.5*	*14*
2.0 – 2.5	40	14	54	23.6	*9.9*	*21*

Table 1. Active power (kW)

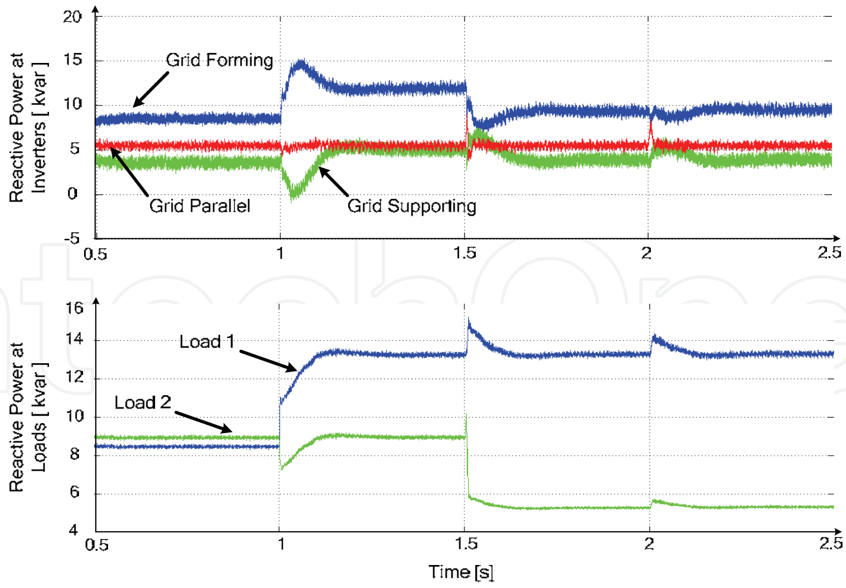

Fig. 36. The reactive power.

Time (s)	$Q_{load\ 1}$	$Q_{load\ 2}$	ΣQ_{load}	*GF*	*GS*	*GP*
0 – 1.0	8.5	9	17.5	8.4	3.8	5.5
1.0 – 1.5	13.2	9	22.2	11.9	5.1	5.5
1.5 – 2.0	13.2	5.2	18.4	9.3	3.87	5.5
2.0 – 2.5	13.2	5.2	18.4	9.3	3.87	5.5

Table 2. Reactive power (kvar)

Having a look at Fig. 37 we can see the response of the grid forming inverter to the load increase at t=1 second. The inverter will hold voltage constant and the current will increase to satisfy the load demand. Another example is the responses of the grid supporting inverter shown in Fig. 38, when the load decreases, which is the case at t=1.5 seconds. We can see that the voltage will stay constant as forced by the grid forming inverter while the supplied current will decrease as signaled by the supervisory unit.

Since the grid parallel unit is not dependent on the load and is not actively dispatchable by the grid we can see in Fig. 39 that it does not respond to the load steps in the grid and instead of that keeps supplying the same amount of current all the time. This matches the definition of grid parallel inverter since it is not actively controlled by the grid.

Having a look at the load voltage and current response at t=1 second when a step happens, see Fig. 40, we can see that the voltage is kept constant all the time by the system and is restored rapidly in case of any load step. This shows the controller capabilities to supply a high power quality.

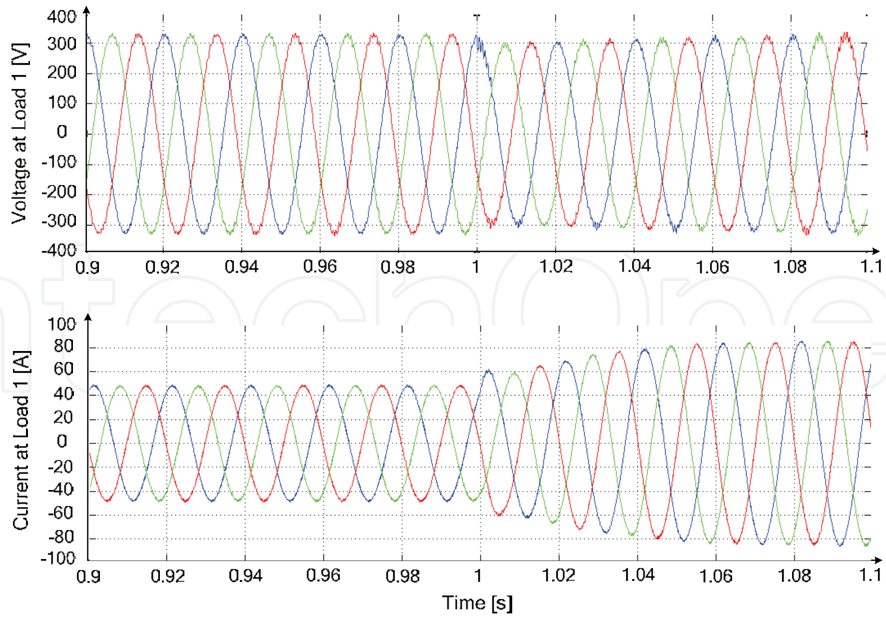

Fig. 37. Voltage and current of grid forming at first step.

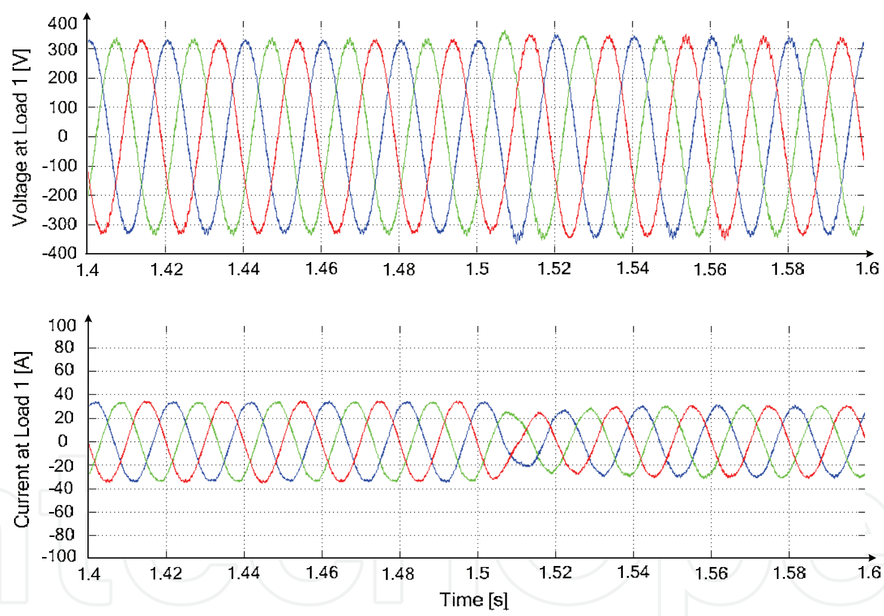

Fig. 38. Voltage and current of grid supporting at second step.

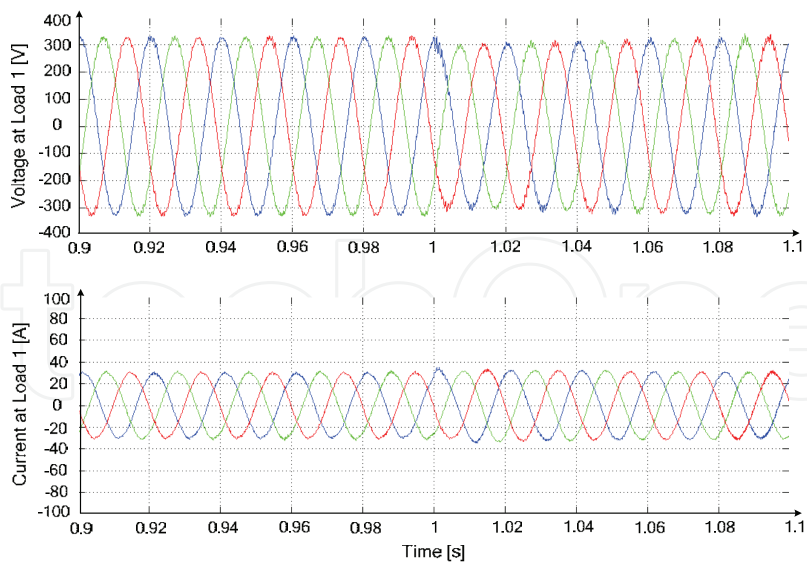

Fig. 39. Voltage and current of grid parallel at first step.

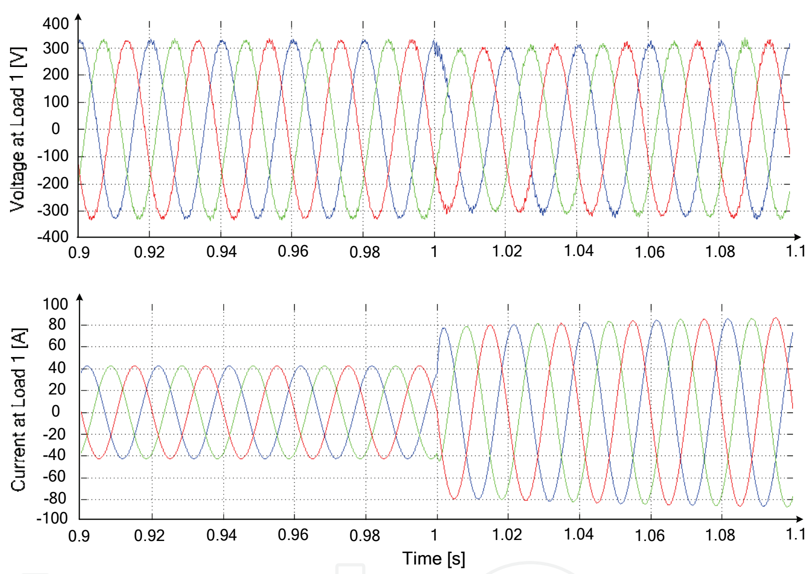

Fig. 40. Voltage and current at load one during first step.

7. Conclusion

Our present and future power network situation requires extra flexibility in the integration of distributed generation more than ever. Mainly for the small and medium energy converting systems including intelligent control and advanced power electronics conversion systems.

This research study showed the visibility of various methods of forming an electric power supply system by paralleling power electronic inverters. These methods foundation is based on the conventional grid control methodologies. This research addressed mainly the control issues related to future modular distributed power systems with flexible power electronics inverters as front-end.

This work introduced a variety of standardized modular architectures and techniques for distributed intelligence and smart power systems control that can be used to build an electric power supply system by paralleling power electronic inverters. It launched different and various robust control approaches based on the feeding mode definition for a realistic distributed power system with power electronics inverters as front-end. These control strategies guarantee real modularity, high reliability and true redundancy. The proposed control architectures maintain the three phase voltages and frequencies in the grid within certain limits and provide power sharing between the units according to their ratings.
The research led to an original philosophy for supervisory control and energy management of an Inverter-based modular smart grid for distributed generation applications. The method developed is based on the feeding modes definition and supports the active integration of the inverters (energy converting systems & renewable energy sources). The main control tasks (voltage/frequency control) are done locally at the inverters to guarantee modularity and to minimize communication bandwidth requirements. The supervisory control is used for dispatching and optimization control. It can also include real time pricing and meteorological forecasting. The concept was developed and tested for three-phase, three-wire and four-wire systems.

In this study, the general control functions and the system behaviour have been investigated. With this investigation it has been shown that the realisation of smart power systems in general through the new system philosophy is possible and advantageous.

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Energy Management

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Forecasts point to a huge increase in energy demand over the next 25 years, with a direct and immediate impact on the exhaustion of fossil fuels, the increase in pollution levels and the global warming that will have significant consequences for all sectors of society. Irrespective of the likelihood of these predictions or what researchers in different scientific disciplines may believe or publicly say about how critical the energy situation may be on a world level, it is without doubt one of the great debates that has stirred up public interest in modern times. We should probably already be thinking about the design of a worldwide strategic plan for energy management across the planet. It would include measures to raise awareness, educate the different actors involved, develop policies, provide resources, prioritise actions and establish contingency plans. This process is complex and depends on political, social, economic and technological factors that are hard to take into account simultaneously. Then, before such a plan is formulated, studies such as those described in this book can serve to illustrate what Information and Communication Technologies have to offer in this sphere and, with luck, to create a reference to encourage investigators in the pursuit of new and better solutions.

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