PARALLEL OPERATION OF POWER CONVERTERS FOR APPLICATIONS TO DISTRIBUTED ENERGY SYSTEMS

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I. INTRODUCTION

Recently interest in Distributed Energy Systems (DES) is increasing, particularly onsite generation. This interest is because larger power plants are economically unfeasible in many regions due to increasing system and fuel costs, and more strict environmental regulations. In addition, recent technological advances in small generators, Power Electronics, and energy storage devices have provided a new opportunity for distributed energy resources at the distribution level, and especially, the incentive laws to utilize renewable energies has also encouraged a more decentralized approach to power delivery [1-16].

There are many generation sources for DES: conventional technologies (diesel or natural gas engines), emerging technologies (microturbines or fuel cells or energy storage devices) [1, 3, 5, 7, 8, 9, 10, 11, 13, 14], and renewable technologies (small wind turbines or solar/photovoltaics or small hydro turbines) [4, 5, 11]. These DES are used for applications to a standalone [12, 13, 14], a standby [3, 10], a grid-interconnected [1, 14], a cogeneration [8, 9, 10], peak shavings [3], etc. and have many advantages such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, expandability, etc. So many utility companies are trying to construct small distribution stations combined with several DES available at the regions, instead of large power plants.

Basically, these technologies are based on notably advanced Power Electronics because all DES require Power Converters, interconnection techniques, and electronic control units. That is, all power generated by DES is generated as DC Power, and then all the power fed to the DC distribution bus is again converted into an AC power with fixed magnitude and frequency by control units using Digital Signal Processor (DSP). So improved power electronic technologies that permit grid interconnection of asynchronous generation sources are definitely required to support distributed generation resources [1, 2, 3, 4, 7, 9, 10, 12, 14, 15, 16].

The research works in the recent papers about DES focus on being utilized directly to a standalone AC system or fed back to the utility mains. That is, when in normal operation or main failures, DES directly supply loads with power (standalone mode or standby mode), while, when DES have surplus power or need more power, this system operates in parallel mode to the mains. Therefore, in order to permit to connect more generators on the network in good conditions, a good technique about interconnection with the grid and voltage regulations should overcome the problems due to parallel operation of Power Converter for applications to DES.

II. OBJECTIVES

The objective of this paper is to provide the extended review about interconnection and control technology for parallel operation of Power Converter for applications to Distributed Energy Systems, and to summarize some conventional approaches to power system operations and control at the distribution level. Moreover, a new configuration and future research works to enhance the performance of distributed generation systems are suggested.

III. DISTRIBUTED ENERGY SYSTEMS

Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed generation resources around the world. As shown in Fig. 1, the currently competitive small generation units and the incentive laws to use renewable energies force electric utility companies to construct an increasing number of distributed generation units on its distribution network, instead of large central power plants. Moreover, DES can offer improved service reliability, better economics and a reduced dependence on the local utility. Distributed Generation Systems have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generation as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis.

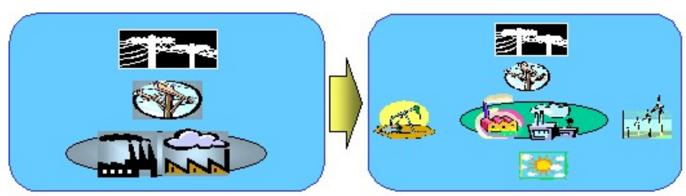

Fig. 1 A large central power plant and distributed energy systems

Meanwhile, recently, the use of Distributed Energy Systems under the 500 kW level is rapidly increasing due to recent technology improvements in small generators, power electronics, and energy storage devices. Efficient clean fossil-fuels technologies such as micro-turbines and fuel cells, and environmentally friendly renewable energy technologies such as solar/photovoltaics, small wind and hydro are increasingly used for new distributed generation systems. These DES are applied to a standalone, a standby, a grid-interconnected, a cogeneration, peak shavings, etc. and have a lot of benefits such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, expandability, etc.

The major Distributed Generation technologies that will be discussed in this section are as follows: micro-turbines, fuel cells, solar/photovoltaic systems, and energy storage devices.

Micro-turbines, especially the small gas fired micro-turbines in the 25-100 kW that can be mass-produced at low cost have been more attractive due to the competitive price of natural gas, low installation and maintenance costs. It takes very clever engineering and use of innovative design (e.g. air bearing, recuperation) to achieve reasonable efficiency and costs in machines of lower output, and a big advantage of these systems is small because these mainly use high-speed turbines (50,000-90,000 RPM) with air foil bearings. Therefore, microturbines hold the most promise of any of the DES technologies today [1, 5, 7, 8, 9, 11, 13, 14].

Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or produced from natural gas, or liquid fuels such as alcohols, or gasoline. Each unit ranges in size from 3 – 250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid cell are commercially available in the range of the 200 kW, while solid oxide and molten carbonate cell are in a pre-commercial stage of development. The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW, hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon [5, 11].

Mixed micro-turbine and fuel cell systems will also be available as a distributed generation source. Recently, a solid oxide fuel cell has been combined with a gas micro-turbine creating a combined cycle power plant. It has expected electrical efficiency of greater than 70 %, and the expected power levels range from 250 kW to 2.5 MW [11].

Solar/photovoltaic systems may be used in a variety of sizes, but the installation of large numbers of photovoltaic systems is undesirable due to high land costs and in many geographic areas with poor intensity and reliability of sunlight. In general, almost one acre of land would be needed to provide 150 kW of electricity, so solar/photovoltaic systems will continue to have limited applications in the future [11].

Energy storage devices such as ultracapacitors, batteries, and flywheels are one of the most critical technologies for DES. In general, the electrochemical capacitor has high power density as well as good energy density. In particular, ultra-capacitors have several benefits such as high pulse power capacity, long lifetime, high power density, low ESR, and very thin and tight. In contrast, batteries have higher energy density, but lower power density and short lifetime relative to ultra-capacitor. So hybrid Power System, a combination of ultra-capacitor and battery, is strongly recommended to satisfy several requirements and to optimize system performance. Recently storage systems are much more efficient, cheaper, and longer than five years ago. In particular, flywheel systems can generate 700 kW for 5 seconds, while 28-cell ultracapacitors can provide up to 12.5 kW for a few seconds [11].

In the past, the electric utility industry did not offer various options that were suited for a wide range of consumer needs, and most utilities offered at best two or three combinations of reliability-price. However, the types of modern DES give commercial electric consumers various options in a wider range of reliability-price combinations. For these reasons, DES will be very likely to thrive in the next 20 years, and especially, distributed generation technologies will have a much greater market potential in areas with high electricity costs and low reliability such as in developing countries.

IV. Problem Statements

DES technologies have very different issues compared with traditional centralized power sources. For example, they are applied to the mains or the loads with voltage of 480 volts or less; and require power converters and different strategies of control and dispatch. All of these energy technologies provide a DC output which requires power electronic interfaces with the distribution power networks and its loads. In most cases the conversion is performed by using a voltage source inverter (VSI) with a possibility of pulse width modulation (PWM) that provides fast regulation for voltage magnitude [11].

Power electronic interfaces introduce new control issues, but at the same time, new possibilities. For example, a system which consists of micro-generators and storage devices could be designed to operate in both an autonomous mode and connected to the power grid. One large class of problems is related to the fact that the power sources such as micro-turbines and fuel cell have slow response and their inertia is much less. It must be remembered that the current power systems have storage in generators' inertia, and this may result in a slight reduction in system frequency.

As these generators become more compact, the need to link them to lower network voltage is significantly increasing. However, without any medium voltage networks adaptation, this fast expansion can affect the quality of supply as well as the public and equipment safety because distribution networks have not been designed to connect a significant amount of generation. Therefore, a new voltage control system to facilitate the connection of distributed generation resources to distribution networks should be developed.

In many cases there are also major technical barriers to operating independently in a standalone AC system, or to connecting small generation systems to the electrical distribution network with lower voltage, and the recent research issues includes:

1. Control strategy to facilitate the connection of distributed generation resources to distribution networks [2, 15].
2. Efficient battery control [4].
3. Inverter control based on only local information [11].
4. Synchronization with the utility mains.

5. Compensation of the reactive power and higher harmonic components [12, 15, 19-30].

6. Power Factor Correction [14, 19-22].

7. System protection [1, 3, 11].

8. Load sharing [23-30].

9. Reliability of communication [3, 4, 11].

10. Requirements of the customer [3, 5, 11, 16].

DES offers significant research and engineering challenges in solving these problems. Moreover, the electrical and economic relationships between customers and the distribution utility and among customers may take forms quite distinct from those we know today. For example, rather than devices being individually interconnected in parallel with the grid, they may be grouped with loads in a semi-autonomous neighborhood that could be termed a microgrid is a cluster of small sources, storage systems, and loads which presents itself to the grid as a legitimate single entity. Hence, future research work will focus on solving the above issues so that DES with more advantages compared with tradition large power plants can thrive in electric power industry.

V. Problem Description

These new distributed generations interconnected to the low grid voltage or low load voltage cause new problems which require innovative approaches to managing and operating the distributed resources. In the fields of Power Electronics, the recent papers have focused on applications of a standby generation, a standalone AC system, a combined heat and power (cogeneration) system, and interconnection with the grid of distribution generations on the distribution network, and have suggested technical solutions which would permit to connect more generators on the network in good conditions and to perform a good voltage regulation. Depending on the load, generation level, and local connection conditions, each generator can cause the problems described in the previous chapter. The main goals which should be achieved will thus be: to increase the network connection capacity by allowing more consumers and producer customers connection without creating new reinforcement costs, to enhance the reliability of the systems by the protections, to improve the overall quality of supply with a best voltage control.

A. Configurations for DES

1) Case I: A Power Converter connected in a Standalone AC System or in Parallel with the Utility Mains [1, 2, 7, 9, 10, 13, 14]

Fig. 2 to 4 show a distributed power system which is connected to directly load or in parallel with utility mains, according to its mode. This system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, output sensor (V, I, P), and a DSP controller. In the Figures, a distributed generator may operate as one of three modes: a standby, a peak shaving, and a standalone power source.

In a standby mode shown in Fig. 2, a generator set serves as a UPS system operating during mains failures. It is used to increase the reliability of the energy supply and to enhance the overall performance of the system. The static switch SW 1 is closed in normal operation and SW 2 is open, while in case of mains failures or excessive voltage drop detection SW 1 is open and SW 2 is simultaneously closed. In this case, control techniques of DES are very similar to those of UPS. If a transient load increases, the output voltage has relatively large drops due to the internal impedance of the inverter and filter stage, which frequently result in malfunction of sensitive load.

Fig. 3 can serves as a peak shaving or interconnection with the grid to feed power back to mains. In both modes, the generator is connected in parallel with the main grids. In a peak shaving mode, this generator is running as few as several hundred hours annually because the SW 1 is only closed during the limited periods. Meanwhile, in an interconnection with the grid, SW 1 is always closed and this system provides the grid with continuous electric power. In addition, the converter connected in parallel to the mains can serve also as a source of reactive power and higher harmonic current components.

In a standalone AC system shown in Fig. 4, the generator is directly connected to the load lines without being connected to the mains, and it will operate independently. In this case, the operations of this system are similar to a standby mode, and it serves continuously unlike a standby mode and a peak shaving mode.

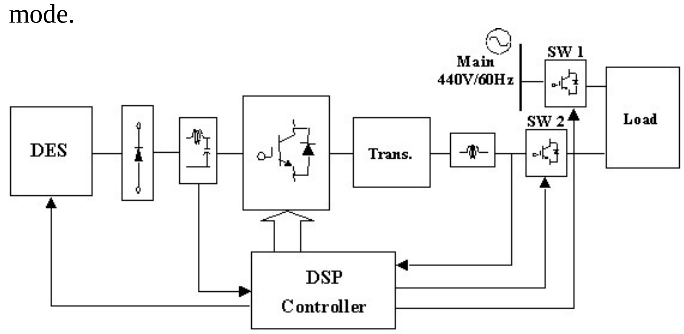

Fig. 2 Block diagram of a standby mode

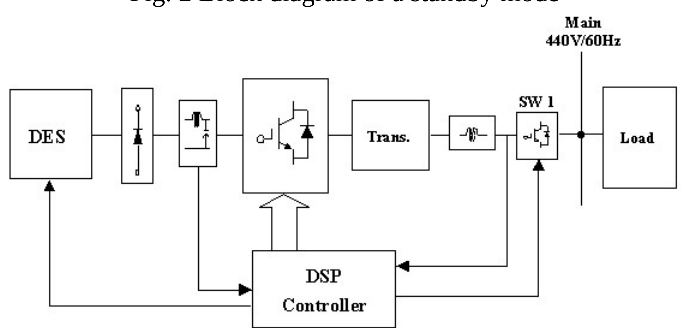

Fig. 3 Block diagram of a peak shaving mode

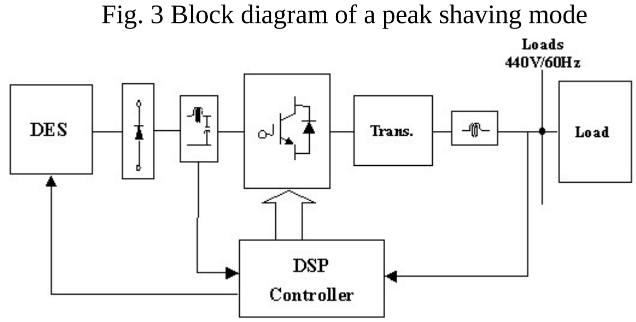

Fig. 4 Block diagram of a standalone mode

As shown in Fig. 2 to Fig. 4, the output voltage of the generator is fed to a DC/AC converter that converts a DC output of the generator to be fixed voltage and frequency for utility mains or loads. The DSP controller monitors multiple system variables on a real time basis and executes control routines to optimize the operation of the individual subsystems in response to measured variables. It also provides all necessary functions to sense output voltages, current, and power, to operate protections, and to give reference signals to regulators. The output power of the converter is controlled according to the reference signal of the control unit. As described above, in order to compensate for reactive power and higher harmonic components or to improve power factor, the active power (P) and reactive power (Q) should be controlled independently. Moreover, the above system needs over-dimensioning some parts of the power converter in order to produce reactive power by the converter at rated active power. Because a power converter dimensioned for rated current can supply reactive power only if the active component is less than rated. Therefore, a control strategy easy to implement is required to ensure closed loop control of the power factor and to provide a good power quality.

In case that a generator is used for distributed generation systems, the recent research focuses are summarized as follows:

1. Control strategy which permits to connect more generators on the network
2. Compensation of the reactive power and higher harmonic components
3. An active power (P) and a reactive power control (Q) independently
4. Power factor correction
5. Synchronization with the utility mains
6. System protections

2) Case II: Power Converters supplying power in a standalone mode or feeding it back to the utility mains [4, 5, 6, 8, 11, 12, 15, 16, 17]

Fig. 5 shows a block diagram of multiple power converters for a standalone AC system or feeding generated powers back to the utility mains. If all generators are directly connected to the loads, the systems operate as a standalone AC system. Meanwhile, if these are connected in parallel to the mains, these provide the utility grids with an electric power. Each system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, a control unit (DSP), a static switch (SW 1) and output sensors (V, I, P). The function of the static switch (SW 1) is to disrupt the energy flow between the generator and mains or loads in the case of disturbances in the mains voltage. As shown in Fig. 5, this configuration is very similar to parallel operation of multiple UPS systems except that the input sources of inverters are independent generation systems such as microturbines, fuel cells, and photovoltaics, etc. instead of utility mains.

In case of parallel operation of UPS systems [18, 23-30], a recent critical research issue is to share linear and nonlinear load properly by each unit. In general, the load sharing is mainly influenced by nonuniformity of the units, component tolerance, and line impedance mismatches. Another issue is a proper control scheme without any control interconnection wires among inverters because these wires restrict the location of the inverter units as well as these can act as a source of the noise and failure. Moreover, in three-phase systems they could also cause unbalance and draw excessive neutral currents. Even if conventionally passive L-C filters were used to reduce harmonics and capacitors were employed to improve the power factor of the ac loads, passive filters have the demerits of fixed compensation, large size, and resonance. Therefore, the injected harmonic, reactive power burden, unbalance, and excessive neutral currents definitely cause low system efficiency and poor power factor. In particular, a power factor can be improved as AC/AC power converters function a complete active filter [19-22] for better power quality and the above problems should be overcome by a good control technique to assure the DES to expand increasingly around the world.

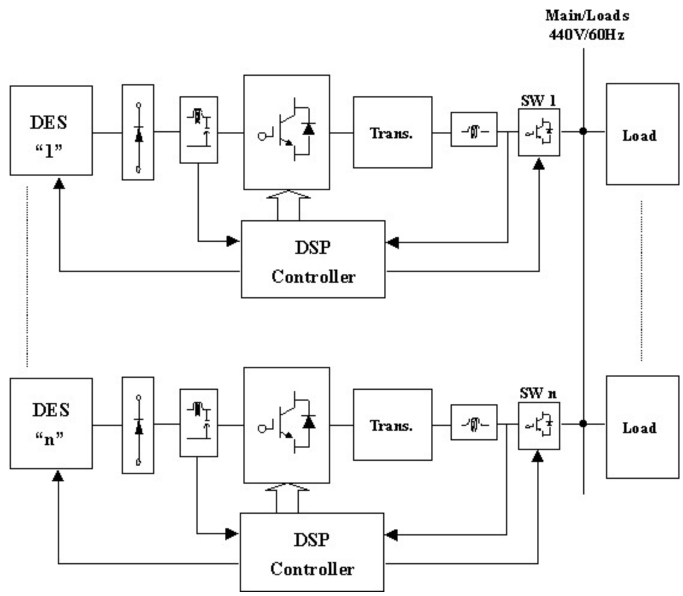

Fig. 5 Block diagram of power converters connected in parallel

So the above issues can be applied to distributed power systems similarly, and the recent research focuses are summarized as follows:

1. Standardized DES modeling using the software tools
2. Equal load sharing such as the real and reactive power, the load harmonic current among the parallel connected inverters.
3. Connection capability of more DES to the utility mains in best conditions
4. Independent P, Q control of the inverters
5. Power factor correction
6. Reduction of Total Harmonic Distortion (THD).

VI. Proposed Configuration

The recent research papers have mainly discussed the operation of single distributed generator for applications to a cogeneration system, a standalone AC system, and a standby generation, or the interconnection with the grid for feeding an electric power back to the mains using several distribution power resources. However, there are no good papers which suggested the standardized models for the reliable simulation of DES which can operate as a standalone AC system, a standby generation, or the interconnection with the grid according to customers' needs in a distributed system using several distributed generation resources. The design methods based on extensive use of simulation software are very important to design the controller, to optimize the system parameters, and to predict the overall performance.

The new configuration is proposed for various applications in Fig. 6. This figure shows a block diagram of the hybrid power system which combines several distributed energy sources into one system for a standalone mode or feeding it back to the utility mains. The hybrid power system should be developed to maximize the benefits of each power generating sources while minimizing the distinct disadvantages of each power source. As shown in Fig. 6, this configuration is a combined diagram of Fig. 2 to Fig. 5. Each generator consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, a control unit (DSP), two static switches (SW 1, SW 2) and output sensors (V, I, P). Each distributed generation system also is connected to utility mains and load lines by fast-acting static power switches in order to rapidly change a standalone mode or a parallel mode with mains. In case that some generators supply extra power with the mains, SW 1 is closed and SW 2 is open. In a standalone mode, SW 1 is open and SW 2 is closed. When the loads need more electric power, both SW 1 and SW 2 are closed, and during malfunctions of any generator both SW 1 and SW 2 are turned off. The characteristic of this system can be used as several modes by one system combined with several distributed energy resources. That is, some generator can be used for a standalone AC system, and another for a grid-interconnection.

This hybrid system should include the following issues. An electronic control unit (DSP) monitors multiple system variables on a real time basis and executes control routines to optimize the operation of the individual subsystems in response to measured variables. For example, the DSP controller provides all necessary functions to sense output voltages, current, and power, to operate protections, to give reference signals to regulators, and to receive control reference signals from a Supervisory Control Unit (SCU). Moreover, SCU communicates with each DSP controller and Distributed Control Center (DCC), which is a remote central computer, via LAN/modem or radio link to allow interactive control of DES and data collection from those on a real time basis or as a pre-programmed data transfer.

As stated above, the DSP based controller is the most critical component for successful operation of the distributed power systems. The controller controls all for the good qualified power which is fed into the hybrid system from various sources and which is supplied to the loads. In particular, the efficient control of the battery is very important to increase the service life of the battery and lower an overall life cycle cost of energy. Because any errors in control that affect battery efficiency and shorten the lifetime of the batteries have a tremendous influence on total hybrid system costs. The DSP controller not only has to monitor power inputs from the various sources which are simultaneously charging the batteries, but it also has to monitor the power leaving the battery bank. In addition, the controller also has to monitor the ambient temperature and the age of the batteries. From both the measured and archived data, the DSP controller will mathematically determine the instantaneous state of charge of the battery bank and execute algorithms to control the charge/discharge cycle of the battery bank. Consequently, the control routine which optimizes the operation of the batteries and extends the service life of the battery bank, will have major impact on the life cycle cost of the system. The SCU is interactive with several power sources in this system, monitoring the subsystems to optimize efficiency, minimize cost, and perform operational routines based on real time conditions.

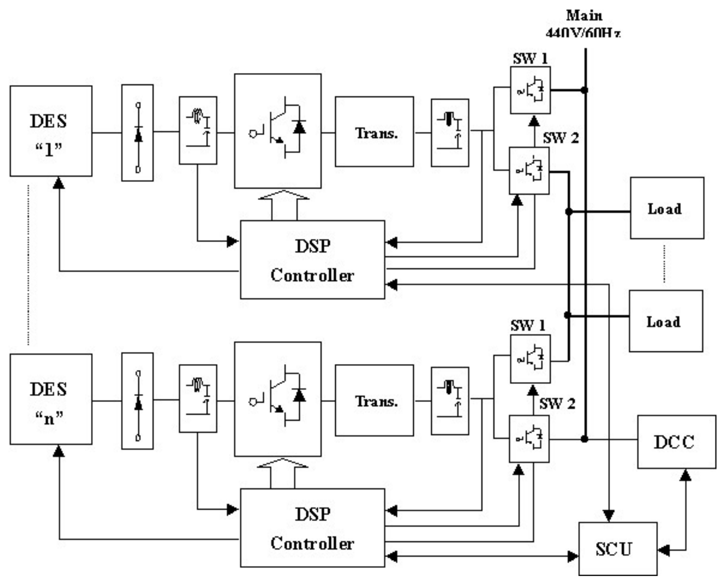

Fig. 6 Block diagram of the proposed power converters

In addition, AC/AC power converters connected in parallel to the mains can serve also as a source of reactive power and higher harmonic current components. Therefore, in order to compensate for reactive power or to improve power factor, the active power (P) and reactive power (Q) should be controlled independently, and AC/AC power converters should function a complete active filter.

As we expect, the characteristics and research issues of this system are similar to the combinations of those of two previous systems. The above research issues first have to be implemented by simulation programs using Matlab/Simulink, Saber, and Pspice, and then should be proven by test beds in a real environment.

VII. Future Research

In order for DES to be used for wide applications around the world, many technical issues should be carried out by advanced control strategies. Based on the previous chapters, the future research works are summarized as the follows:

1. Standardized modeling for DES, optimization of the system parameters, and optimal design of controllers using software tools such as Pspice, Matlab/Simulink, Saber

2. Efficient battery control strategies to increase the lifetime of the battery and then reduce the system costs

3. Methods compensating for reactive power, harmonic current components, and unbalanced loads and improving a power factor

4. Control techniques of load sharing uniformly dependent on the capacities: active power, reactive power, harmonic current components

5. A dynamic voltage regulation depending on loads and generation variations

6. Modular inverter development for customer requirements

7. Schemes to damp disturbances from line faults to improve dynamic security

8. Short pay back time on investment

9. Connection capability of more DES to the utility mains in best conditions

10. Reliability of communications between each DES and Supervisory Control Unit, and Supervisory Control Unit and Distributed Control Center using radio and wire link

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