HYBRID PV – DIESEL POWER GENERATOR : DESIGN CRITERIA AND PRELIMINARY PERFORMANCE ANALYSIS

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Abstract: The paper deals with how a Virtual Power Distribution System can be realized using several Hybrid Power Generators remotely controlled through PSTN or Wireless Phone Service (GSM or GPRS). A network of power management nodes capable of supplying electric power anywhere in the territory can be virtually connected to a central management centre from which energy billing, production monitoring and remote maintenance can be assured.

Keywords: Back-up Systems, Energy distribution, Environmental Engineering, Power generation, Renewable Energy System, Solar Energy.

1. INTRODUCTION

Renewable Energy Source (RES), primarily solar and wind sources, plays a relevant role in the world as preferred power generation solution to reduce CO2 emission, to improve quality of the air, and also as viable solution to give electrical energy to people in the developing countries or where the electric distribution network is missing or unreliable.

Wind power generation plays an important economical role: at the end of year 2000 it was installed and operating 17500 MW in the world, 2600 MW in US and 13000 MW in Europe (6100 MW in Germany, 2400 MW in Spain, 2300 MW in Denmark).

Photovoltaic power (PV) generation data shows a lower development stage mainly due to the high cost of the installations with respect to the produced energy. In the year 1999 the photovoltaic energy production in Europe was 0,40% of total renewable energy sources, while wind energy production was 1,40% of total RES production.

Nevertheless photovoltaic power represents today a viable solution for distributed generation. By connecting to the electrical grid several small size units, delivering the excess power with respect to local consumption, which could not be utilized in the place of production, the losses due to transportation of the electrical are reduced, and the availability of the electrical energy when solar power input is lower than the required, is assured by the grid.

When concentrated production of large power of photovoltaic and wind is considered, some problems arise. If the renewable sources power is a significant part (more than 20%) of the total power generation capability of the network (e.g. island network, local network weakly connected to main distribution center, etc…), the intrinsic variability of the wind and photovoltaic power produces instability phenomena in the electrical network. Such instability highly reduce the quality of the electrical energy and limit the amount of usable renewable power.

Moreover the weakly connected network is often unreliable, and when public distribution network is down, uninterruptible power cannot be assured by conventional grid-connected PV generators. Such systems require grid connection to operate: they are able to feed power only over a reference AC voltage source and no local storage of energy is performed in order to accommodate the instantaneous difference between variable produced and consumed power.

The hybrid PV-Diesel power generator presented in the paper was designed to solve all such problems. It is most suitable for small-medium size users who want to conjugate uninterruptible operation with optimal solar energy exploitation.

The system can potentially satisfy the market demand of widespread small-power plants where it is significant to offer a technologically advanced product, characterized by high efficiency and enough flexibility to adapt to peculiarity of the rural zones in which it will be installed. Such demand, undoubtedly present in the developing countries, should not be overlooked in the developed countries. There are areas in which power distribution is uneconomical or problematic due to particular territory orography or due to environmental restrictions.

Most of those places are tourist spots suffering from a sharp increase of population only during few months on the year, where the power distribution lines, sized according to the resident population, are overloaded by the corresponding consumption peak.

Accumulation and local generation of electric energy, especially making use of renewal resources, represent the best way to solve the problem.

The hybrid PV-Diesel power plants suitable for widespread energy production, is a quite new product in Europe. In recent years a lot of basic research was carried out on different micro power plant components: energy storage systems, energy converter systems and related electronics for power management.

Different demonstrative plants, also big sized, embodying the concept to store in different form the energy coming from renewable resources, were realized.

The presented hybrid PV-Diesel generator was designed as an integrated product, relatively compact and lightweight, capable to produce electricity employing power coming from ecological sources characterized by low environmental impact but discontinuous behavior. The system can store the energy in accumulation systems, and then deliver power, when required, to electric devices. The internal Diesel engine guarantees uninterruptible energy also when renewable sources are longer unavailable than allowed by the energy storage unit and load consumption.

The generator can be installed everywhere, with low transportation and setup costs and it can become the manager and supplier of energy for a small village or an isolated group of houses. Thanks to a particular architecture, the unit allows for completely autonomous operation, and except for the power lines and photovoltaic field, no other installation is required.

The automatic capabilities of the micro power plant are realized by means of an advanced embedded energy manager linked with a data logging and communication system.

In order to accomplish the load power level required by loads, the energy manager provides automatic energy dispatching among the PV field, the energy storage unit and the Diesel engine, assigning priority to the exploitation of the renewable source. Furthermore, basic system operations, such as alarm and faults managements, diesel engine fuel and lubricant supply control and periodic maintenance scheduling are performed by the same embedded energy manager.

The data logging and communication system allows for local or remote supervision and maintenance of the system. A single operator can potentially supervise several units disseminated over large areas.

Remote control allows also to manage a network of micro power plants exactly as a traditional distribution system, formed by several interconnected substations supplied by a virtual large central power plant. Such virtual power plant is represented by the control operation center from which it will be possible in the near future to sell energy to every single user, also through an internet portal.

Since every micro power plant itself generates the energy, the costly and low efficient power distribution lines are avoided. Energy demand can be freely satisfied putting the micro power plants on the territory and issuing an assistance network in charge of making the scarce maintenance activity, mainly consisting on refueling the micro power plant. With the proper sizing of PV field and adequate energy storage system capacity, the need to employ the endothermic generator will seldom arise, and so fuel consumption will be extremely low.

2. THE HYBRID PV-DIESEL GENERATOR OF MONTE AQUILONE: GENERAL DESCRIPTION

In the actual implementation, the hybrid PV-diesel generator realized by ENEA and Elettronica Santerno, installed in the test site of Monte Aquilone near Manfredonia, manages the locally generated power coming from an array of photovoltaic panels. The 50kW nominal power PV field represents the primary renewable energy source of the plant.

The functional block schematic of the hybrid generator is presented in fig. 1. The plug box G1 collects the four PV sub-field. It allows for separate connection of each sub-field and provides overcurrent protection.

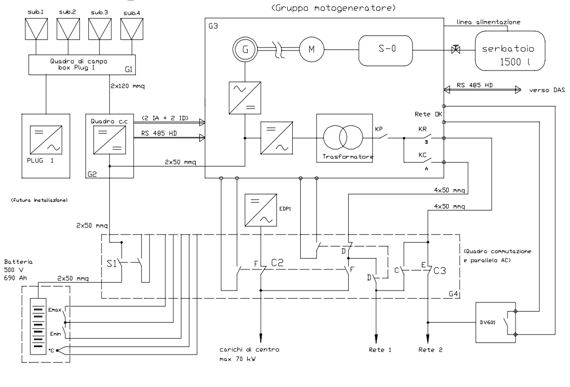

Fig. 1. Hybrid generator functional block schematic

The charge regulator unit G2 embodies a switching current regulator which adapts the variable voltage and variable current PV power to the almost constant voltage of the 500V – 650Ah lead-acid battery stack representing the main energy storage unit of the system. A peculiar characteristic of the boost converted topology adopted for the switching regulator is that during standby operations the solid state internal switch (IGBT) is held closed, and thus the PV field is short circuited. This allows for direct reading of incident illumination level by means of measurement of short-circuited PV field current. The converter start trigger is activated when such current reaches a fixed (parametric) minimum threshold.

The main energy manager unit is contained in G3. It embodies the embedded energy manager controller and two digital-controlled high-efficency three phase inverters connected to the common DC line coming from batteries.

The first 50KVA inverter drives the asynchronous generator which is mechanically coupled with the diesel engine, the second 120kW inverter delivers power to the grid and to the loads through a coupling and isolation transformer.

The generation inverter can directly start the diesel engine temporarily operating as motor drive. As soon as a proper speed threshold is reached, the motor torque is reversed in order to operate as generator, feeding back power from asynchronous motor to the DC line.

The last unit G4 contains all the power switch used to route the electrical power between two grid connections and the load connection. The box G4 was added in such test installation in order to have the possibility to completely bypass the hybrid generator and to put in operation the previous existing solar converter EDP1. In normal installation G4 it is not required: the electric grid is connected directly to the energy manager unit KR contactor, while the loads are connected directly to KC contactor.

The main energy manager unit has two asynchronous RS-485 data connections: the first line is routed toward the data logger and supervisor system (DAS), the second line is used for the charge regulator unit G2 which operates under the supervision of the embedded energy manager controller.

The main nominal specification for the units is reported in the following Tables 1 and 2.

Fig. 2 shows the picture of the main energy manager unit installed in the test site. The upper cabinet contains all the solid state electronics units, while the lower cabinet hosts the diesel engine and the asynchronous generator.

3. THE HYBRID PV-DIESEL GENERATOR SUPERVISION SYSTEM

The user interface of the hybrid PV-diesel generator is realized connecting a PC equipped with Windows

Table 1 Electrical specifications of PV field and Energy Storage

Photovoltaic field	@ STC: Voc= 600V; Pmpp=50KW; Vmpp= 460V; Impp=108A
Charge regulator	Boost converter topology, Iin max = 210A, Pmax = 50kW
Battery	Lead-Acid battery, nominal voltage = 500V, minimum voltage = 450V, max. discharge current = 100A, max .charge current = 69A, Rated battery capacity: 690Ah

Table 2 Main internal units specifications

CPU Dispatcher	Elettronica Santerno “MICROFAST” controller
Generator Inverter	Elettronica Santerno “Sinus VTC” torque control inverter Pn= 50KVA, Iout= 75A Overload 150% during 15 sec
Grid/load Inverter and transformer	Elettronica Santerno “Sunway T” solar inverter Pout= 120kW, Mains voltage 400 Vac±20% , 50 Hz Nominal current = 150A
Asynchronous generator	50kW squirrel cage induction motor, 4 poles 220/380V Δ/Y, Nominal speed 1500RPM
Endothermic engine	“GVM” model D704LT - 2775cc four stroke diesel engine 45 KW @ 1500RPM Continuous power, 12,5lt/h fuel consumption

Fig. 2. The main energy manager unit

operating system through the main serial port. The PC runs a programmable and configurable SCADA (System Control And Data Acquisition) application, tailored for the specific supervision task.

Fig. 3 shows the main screen snapshot of the SCADA application, in which the synoptic schematic of the system is represented.

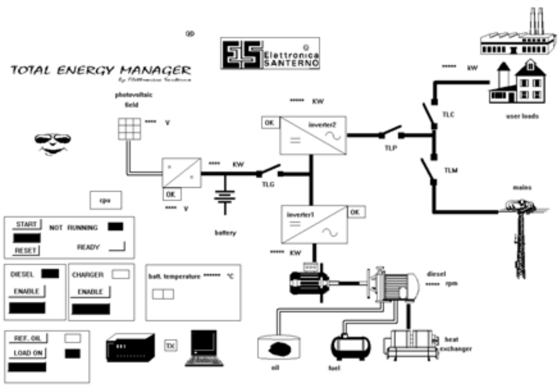

Fig. 3. SCADA application screen snapshot showing synoptic schematic

To trained maintenance personnel, the features of the SCADA, like real time data, alarm list and variables trend selection pages are a very useful tools for easy detection of faulty parts or units in the system.

3. ENERGY DISPATCHING POLITICS

The optimal management of power balance among the energy production units (PV field and diesel generator), the energy storage unit (batteries) and the loads represents the crucial feature of the system. Optimal management means that the power must be mainly sunk from the PV field, thus minimizing the intervention of diesel engine. The eventual excess of PV energy must be mainly stored in the batteries, provided that these are not in full charge state.

Such goals, integrated with units constraint and other system dynamic and reliability consideration, were taken into account during the energy dispatcher design.

The hybrid PV-diesel embedded energy manager dispatching politics are based on three proportional-integral-derivative regulators with saturated output, connected as in the simplified block schematic shown in figure 5.

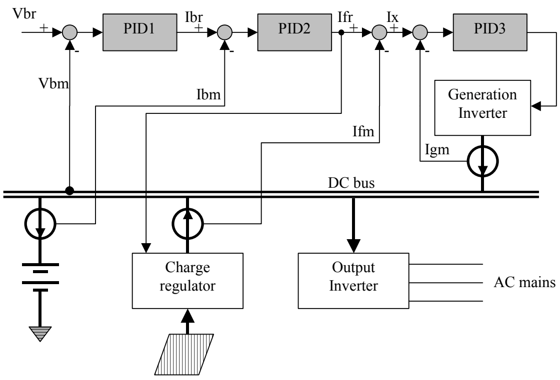

Fig. 4. Simplified block schematic of the energy dispatcher

The scope of the three regulators is outlined in the following:

1. Main battery voltage regulator (PID1) – it provides to regulate the battery charging voltage, and thus the intermediate DC bus voltage, according to the Vbr reference which is function of battery temperature and battery state of charge,
2. Battery current regulator (PID2) – it provides to regulate the battery current by limiting the maximum charging current during the bulk charge phase,
3. Generator power regulator (PID3) – it provides to regulate the current toward the intermediate DC bus voltage generated by the group diesel engine – asynchronous generator and generation inverter.

There are several working conditions for the energy manager. Depending on the multiple combinations derived from the availability of solar power, the state of charge of the batteries and the user request, the energy manager dispatcher provides to set the system status accordingly.

To simplify, there are four main working conditions, outlined below:

a. Battery voltage below minimum value (battery needs recharging) and enough power from the PV field: the PID1 regulator generates a positive battery recharging current setpoint (Ibr) which is managed by the PID2 regulator. The charge regulator setpoint (Ifr) is raised accordingly, and if the PV power is enough, the battery is charged with constant current. If other loads are not present in the common DC bus, the battery charger output current (Ifm) equates the battery charging current (Ibm). If some amount of load is required (the output inverter delivers power to the grid or to the loads), the PID2 reacts raising the charge regulator setpoint (Ifr).
b. Battery voltage below minimum value (battery needs recharging) and not enough power from PV field: If the PV generated power is not enough, the charge regulator setpoint (Ifr) cannot be followed, and so an error results by comparing Ifr and the charge regulator output current (Ifm). When the error signal Ix = Ifr – Ifm, results greater than zero for a sufficient amount of time, the diesel engine start is triggered. Ix is used also as setpoint for the PID3 regulator which manages the generated power by comparing the generation inverter measured output current (Igm) with the reference Ix.
c. Battery voltage at the nominal level (battery at nominal charge), power required by the loads and battery discharge enabled: In such condition the power required can be derived from the batteries and/or from the PV field. The power delivered to the loads initially comes from the battery because the battery current setpoint (Ibr) is forced to the (negative) nominal discharge current value. Two sub-conditions can be met:
   - c1. The power required by the loads results in a battery discharge current below the nominal discharge current value; the battery is thus discharged until its voltage falls below the threshold at which the recharging, according to items a) or b), is triggered.
   - c2. The power required by the load results in a battery discharge current greater than the nominal discharge current value; the resulting error is managed by the PID2 regulator which sends a positive charge regulator setpoint (Ifr). If the PV power is enough the condition lasts with the battery discharged at programmable rate while the remaining power is furnished by the PV field through the charge regulator. When the PV power is not enough, the error signal Ix = Ifr – Ifm results greater than zero, triggering the diesel engine start according to item b).
d. Battery voltage at the nominal level (battery at nominal charge), power required by the loads and battery discharge not enabled: When the battery discharge is not enabled, the Ibr is forced to zero, so any load request results, through the regulator PID2, in a charge regulator setpoint (Ifr) greater than zero. The request is treated as outlined on item c2), and the power for the loads comes entirely from PV field, if available, and/or from diesel generator if not sufficient or unavailable.

4. PRELIMINARY EVALUATION TEST

In order to verify the system short-term behavior, a daily load profile, characterized by a peak power of 62kW and average power of 21kW, was imposed to output inverter. With reference to a typical sunny day, the following graphs show the renewable power produced by the photovoltaic field, the current sharing on the common DC bus managed by the energy dispatcher and the diesel engine instantaneous speed and power.
It must be noticed that in the middle of the day the user makes some intervention overriding the energy dispatcher controls. In order to test the behavior of the system and the recovery from situation like abrupt PV power decay, several tests switching from manual to automatic mode were carried. The data logging system, from which the above graphs were obtained, records all the history of the variables.
For instance it can be noticed that at sunset the PV power decays, while the load remains almost constant. The battery current changes sign, and the battery voltage decreases until the diesel engine was automatically started.

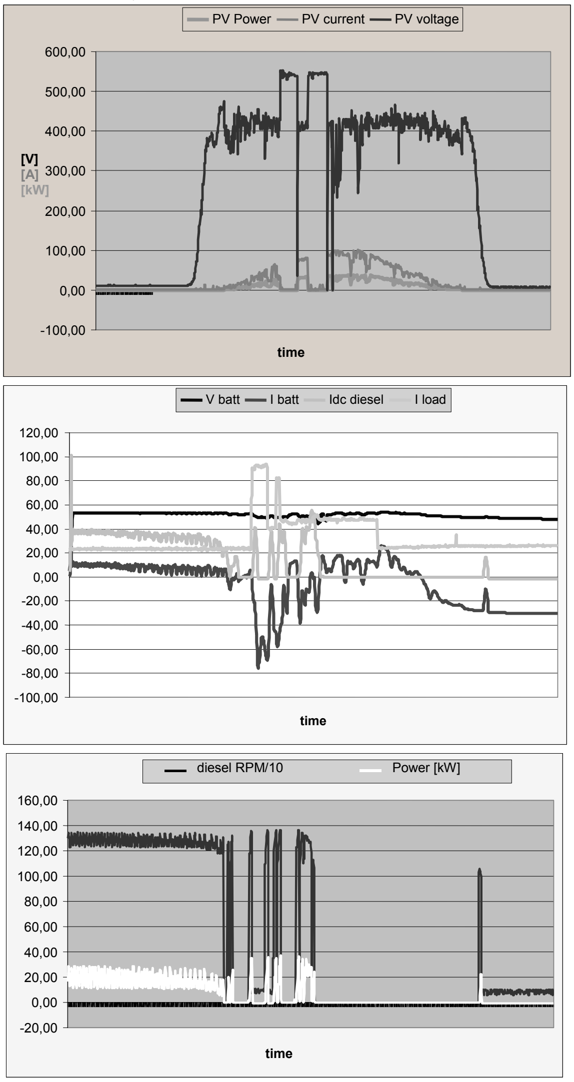

Fig. 5. Renewable power produced, current sharing on common DC bus and diesel engine speed and power as a functions of the time

After few minutes of diesel engine operation, the user overrides the control in order to stop engine during night and to experience a full discharge of the battery stack.

4.1 Anti Black-Out Solar Hybrid Power Microstation Aladin 2000™ the energy genius

From this experience a new specification has been prepared for a new PV/Wind Hybrid power generating station of reduced power, suited to give full autonomy to small remote utilities as if they were normal grid connected loads. The maximum power of this single phase power station is 9 kW. Higher powers are provided for three phase applications.
The solar/wind hybrid power microstation Aladin™ is the latest solution to the requirements of energy demand to be integrated with renewable, both in grid connection and in stand-alone diffused production.
The power station allows for more utilities and simultaneous consumption without having to modify the existing electric supply contract, to which the power station adds power. The presence of a suitable photovoltaic field ensures the simultaneous operation of domestic utilities and of the air conditioning system, which is often used when the sun is more scorching.
A black-out would not cause any problem to the house and people who have the power station, as the latter continues generating the necessary energy whilst waiting for the electric supplier to solve the problem.
The powerful system of energy calculation and delivery can be programmed for the management of time bands in order to optimise costs and distribute consumption as suitably as possible. The power station can be used as Stand Alone system for remote utilities.

Fig.6 Picture of the Product Developed:

According to the results of the described experimentation, many functions have been prepared and applied for the correct operation of normal applications as described as follows.

4.2 Main Functions

Grid Supervision. In compliance with CEI 11-20, DK5950 and IEC61727. The inverter always checks the grid voltage, disconnects from it in a safe way and keeps utilities powered.

Peak shaving, power factor correction and time bands. The inverter optimises the absorption from the grid by reducing the peaks of absorbed power and correcting the utility's power factor. 6kVApeak demands can be powered with a lower installed grid power and the power can be managed according to time bands.

Load voltage stabilisation in Grid Connected operation. When the grid voltage differs from the rated voltage by more than 5%, the inverter is activated in order to keep the load voltage within the tolerance values (optional). When the grid voltage deviation reaches the values that require the supervisor's operation, the inverter disconnects from the grid, in compliance with the existing regulations.

Anti black-out operation. When the grid voltage is out of tolerance (or absent), the inverter powers the utilities with the energy from the photovoltaic field and/or the storage system. Recovery time of the load voltage is 100ms. If the optional static switch is used, the recovery time is less than 10ms. In this situation the load voltage is stabilised within +/- 1% for currents up to 1.5 times the rated value. A transient overload of 2.5 times the rated current for 1 minute is allowed. In case of failures in the user's system and of serious overloads, the supplied current is automatically limited to the maximum admitted value: if the overload persists for more than one minute, the inverter protects itself by stopping. If the UPS operation lasts for a long time, the auxiliary power unit (optional) is automatically operated before the battery discharge level is excessive, thus safeguarding power continuity to utilities and battery integrity. The power unit can be dimensioned not

according to the 6kVA power, but according to a lower power given by the average power absorbed by the utility and the installed storage system autonomy.
Battery charge check. The equipment checks the battery charge (residual Ah) and charges it automatically when necessary (from the grid, photovoltaic field or power unit)according to the ideal charge profile of the batteries used; the temperature of a positive poleis measured for the compensation of the variations of the voltage thresholds. If different battery configurations are necessary, the system can be integrated with a special battery interface unit.

Interface with photovoltaic field. A part pf the equipment is for the connection with the photovoltaic field: the system can automatically search the Maximum Power Point Tracking condition (MPPT). If the storage system is charged and no energy to grid/load is necessary, the delivered power is reduced in order to prevent the battery from being damaged by overcharge. As an optional component, an electronic board that controls the ground insulation of the poles of the photovoltaic field is available.

Remote Control. The remote control and supervision system is compatible with the similar systems of the PV inverters by Elettronica Santerno Spa, well-known on the PV market.

5. CONCLUSIONS AND PERSPECTIVES

The main functional features of an Hybrid PV-Diesel power plant for the widespread production on the territory of electric energy from renewable sources have been presented. The operating modules of the micro power plant were identified in order to fulfill a virtual distribution network in areas which are hardly or not at all reached by the electric distribution network. The implementation carried out by ENEA and Elettronica Santerno, actually under test in the ENEA Monte Aquilone site, was described. The results of the working tests available until now and relevant to the functioning in grid connected mode with connection to a photovoltaic field show the efficient integration of the energy supplied by the renewable source with the one produced by the endothermic generator. In the perspective, a Hybrid Wind-PV-Diesel power plant can be obtained with a minor modification of the proposed system: a low-power (25kW nominal) wind generator equipped with a simple asynchronous generator can be directly connected to the unit through a switch contactor as alternative to the internal generator. When no PV energy is available and batteries need recharging, (e.g. during night), the presence of wind can be utilized instead of internal diesel engine, extending furthermore the fuel savings.
The installation and maintenance costs of such simple kind of wind generator are relatively low, and in reasonably windy sites it is an investment that can be recovered in few years of operation.