SMALL-SCALE SINGLE PHASE EMBEDDED GENERATORS CONNECTED AT LV

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SUMMARY

Worldwide developments in small-scale embedded generation, focusing on heat-and-power systems and photovoltaic power systems in distribution networks, are surveyed. The heat-and-power systems are based on gas engines, Stirling engines and fuel cells. Technical issues arising from the multiple connection of single phase electrical generation schemes are considered. Typical domestic LV networks and embedded generator load profiles are studied. The implications for a network operator are changes in network voltages, consumer load profiles, substation loading and voltage profiles.

INTRODUCTION

There is growing concern amongst electricity companies about the potential problems that could be caused by multiple connection of single phase electrical generators on the LV distribution network. Small-scale photovoltaic systems and Stirling engine power sources are increasingly becoming a commercial proposition, due to improvements in base technology and advances in power electronic power conversion techniques. Current developments mean that the "off-the-shelf" power controller device will soon be available.

PRODUCT SURVEY

Combined heat and power (CHP) systems, or 'co-generation' schemes, where waste heat from the electricity generation process is used to provide heating have been implemented throughout Europe and in other parts of the world using a range of generator types and energy sources. Most of the schemes are on a much larger scale than individual residential or small commercial properties.

Small-scale heat and power systems are currently based on combustion plant such as gas engines. Stirling engines and fuel cells have the potential to provide CHP at the scale of individual dwellings (micro CHP). Photovoltaic (PV) systems are seen as an alternative source of electrical power. In the following sections, converted and Stirling engines, fuel cells and photovoltaic systems, are considered separately.

Converted Engines

Modified truck engines running on natural gas, with outputs from 38-200 kW, power most existing small-scale CHP. Modified petrol engines are preferred below 50kW. For domestic CHP applications other than district heating, the size range of interest is < 5kW of electrical power. Petrol units of this size are currently marketed by Japanese manufacturers, eg Honda, for stand-alone intermittent use. Recent developments in Germany, have seen the introduction of gas engines based on 5.5kW electrical power, eg Fichtel & Sachs, with a 3kW engine planned. They are, however, too expensive and noisy for domestic installation.

Stirling Engines

The Stirling engine is an external combustion engine invented in Scotland in 1816. It is characterised by an external heat supply which allows the use of any heat source which is at a sufficient temperature level. The engine operates by continuous heating and cooling of a fully enclosed working gas, often helium. The alternate compressing and expanding of the fixed amount of high pressure helium gas is transferred into a rotating movement, to which electric generators can then be connected. Within the closed Stirling cycle, pressure variations of the working gas follow an almost sinusoidal curve, which is one of the reasons for the Stirling engine's low noise level.

The modern development of the Stirling engine was started by Philips in the Netherlands, who now have a production company in the cryogenics field. United Stirling in Sweden was created in 1968 to achieve a small, reliable, low-priced Stirling engine for automotive, solar and submarine applications; commercial success has been achieved in submarine propulsion. TEM in Sweden started development work on a small scale Stirling engine in 1986; Sigma in Norway have acquired manufacturing rights to the TEM engine.

With external combustion being relatively quiet and clean, Stirling engines appear to be best suited for domestic generator applications. Worldwide, significant Stirling engine developments have been achieved in USA, Japan and Sweden (Table 1) [1].

Table 1: Significant worldwide Stirling engine developments

Stirling engine	Electrical power (kW)
WhisperTech	0.8
Sunpower RE100	1.2
Kawasaki Model V	1.2
TEM 1-130	3.75
Mitsubishi NS-03M	3.8
Toshiba NS-03T	4.1
Philips 1-98	15
SPS V-160	15

Fuel cells

Invented in 1839, fuel cells are electrochemical devices which convert the energy of a chemical reaction directly into electricity and heat. Fuel cells using 3 different types of electrolyte are being developed for CHP (Table 2).

Table 2: Main types of fuel cell for CHP

Fuel cell type	Electrolyte	Development stage
PAFC	phosphoric acid	200kW plants in operation
SPFC	solid polymer	orders taken for transport - 200kW
SOFC	solid oxide	1-3kW domestic under investigation

There are at least 10 200kW PAFC plants operating in Europe with fuel cell power plants manufactured by International Fuel Cells (IFC).

SPFC distributed power generating systems using natural gas have not yet been demonstrated, but Dow & Ballard (Canada) demonstrated 5kW and 11kW systems using hydrogen in 1990/91.

A 1kW/3kW residential SOFC is being contemplated by Sulzer-Innotec in Switzerland and Polydyne/Electric Power Research Institute (EPRI)/South Coast Air Quality Management District (SCAQMD) in the USA. Sulzer-Innotec have recently embarked on demonstrations of small systems in selected domestic co-generation applications in Germany; field tests have been operating in Switzerland for a year. Grid connection is also seen as an important area. Sulzer-Innotec are working with utilities to promote the technology with the aim of marketing it from about the year 2001 with the support of 10-20 utilities.

Photovoltaic Systems

The PV cell is a device which acts as a source of electrical power, using a completely renewable power source: visible or UV light. Commercial units are available and many installations exist throughout the world. Their flexibility in terms of series and parallel arrays means that a wide range of power levels is available to suit a variety of needs. This has resulted in a very broad range of applications including commercial and domestic buildings.

In Germany, where there is strong support for the development of PV technologies, the Federal Ministry of Research & Technology (BMFT) and the federal states are together subsidising the installation of small (1-5kW) grid-connected PV systems on the roofs of 2250 homes. There is also a German directive for the operation of systems 5kW in parallel with the low voltage grid [2].

In Switzerland, the installation of domestic grid-connected PV systems is encouraged, and under Project Megawatt over 100 3kW grid-connected PV systems have been installed in residential and business premises.

In Japan, where high land costs make roof-mounted PV systems attractive, an extensive research programme has been undertaken to determine the effects on the grid of large numbers of small household PV systems. This includes the construction of a large experimental array of 100 individual 2kW PV systems, each with its own inverter, by the Kansai Electric utility at its Rokko Island test site. The Japanese government is also planning to support, in its New Sunshine Project, a large demonstration programme that could eventually lead to 70,000 roof-top PV systems. The International Energy Agency PV Power Systems (PVPS) group is the contact for current PV development status.

TECHNICAL STUDIES

Effects on network voltage levels and currents, when embedded generator schemes are added to the network, have been studied at EA Technology. The scope was to investigate the design and technical issues arising from LV single phase generation by study and analysis of typical networks. Scenarios involving PV and CHP schemes were identified for the studies. Domestic LV networks based on simple assumptions for PV and CHP embedded generation schemes were investigated. Varying degrees of concentration of the generators were considered. The studies were carried out using *WinDebut* software and the "*Embedded generation for Debut"* program.

SCENARIOS FOR THE TECHNICAL STUDIES

It was felt that investigations into the effects on electricity networks of embedded generation schemes such as CHP and PV were needed, as there is a growing development of such schemes in the domestic market. The size of generation and connection, although limited effectively by the capacity of the cable to which they would be connected, is mainly dictated by the technology at present. The number and location of such connections, however, is not.

The energy demand and characteristics of these schemes differ from conventional load/energy curves. It is the combined effect of these demand curve differences and the generator export power on network load flow and fault conditions that is the main concern for electricity companies.

Two scenarios for embedded generation growth were identified. These were 1) the occurrence of large groups, possibly newly developed housing estates, incorporating schemes such as the PV installations and 2) the gradual global increase of embedded generation schemes such as CHP, the main area felt to be driving this was older houses with the installation of new heating systems.

NETWORK ASSUMPTIONS FOR STUDIES

One network model could not effectively represent the two generator modelling scenarios, so two networks were created. The networks were produced in *WinDebut*, and the assumptions that were made are described in the following two sections.

Modern Housing Estate

Modern housing estates tend to be built around a number of cul-de-sacs off a main route through an estate with most, if not all, consumers being supplied from the branched cables not the main route.

The basic network topology for this study was taken to be main feeders from the substation, with branches teed off this main feeder. The following assumptions were made in order for the network model to be produced:

- There are no consumers on the main feeder and approximately 50 consumers off each teed branch.
- There are eight branches for the network, giving a total of 400 consumers; four main feeders out of the substation, with two branches teed off each feeder.
- From the tee node on the main feeder, each branch section has 40m of cable with ten consumers; this is five consumers per side of the street giving 8m between houses/loads.
- There are five branch sections for each branch, thus making 200m of cable for 50 consumers.
- Branch tee nodes on the main cable are taken at 50m intervals.
- Customer load profiles remain unchanged with the addition of PV generation schemes due to the weather dependence of the units.
- The annual load consumption is approximately 5600 kWh; *Debut*'s URMC load profile (UnRestricted domestic Medium Consumption) is used, ie approximately 15 kWh per day.

Established Residential Areas

Unlike newer estates, the main roads/routes for these older housing estates are generally considered to be well populated, with consumers on both sides of the main route with few teed branches.

The network topology for this type of arrangement is similar to the previous arrangement, in that four main feeders were supplied out of the substation. The differences occur in the consumer location on the network, most being supplied from the main cable route, ie not the branched cables. The following assumptions were made in order for the network model to be produced:

- Four main feeders with a consumer density of 5 per 50m on each of the feeders.
- Each main feeder has one teed branch with a total of 250m further connected cable and a consumer density of 10 per 50m.
- These houses use 20% more power/energy than modern ones due to their age and less efficient heating system. The total annual consumption therefore is 5600 kWh * 1.2 = 6720 kWh.

TYPICAL EMBEDDED GENERATOR PROFILES

This section describes the steps taken in the production of typical generator profiles used in the *“Embedded generation for Debut”* software.

PV Generator Profiles

It is believed that PV embedded generation will occur in new housing estates, ie installed when the houses are built, and therefore will occur in large groups rather than randomly spread.

The expected capacity from such domestic PV systems is considered to be 1kW, and unlike schemes such as combined heat and power, its output is variable and very weather dependent. Trials show that the average annual generation from a domestic PV scheme based in Britain is around 800 kWh per year.

To determine a suitable simple daily generation profile, the following assumptions were made:

- 1kW of generation over 365 days = 8760 kWh p.a.

- As the device is totally light dependant, the device produces an output from 9am till 5pm (8h) ⇒ 8*1kW*365 = 2920 kWh p.a.
- During Nov, Dec, Jan & Feb, the device is not producing an output ⇒ 8 months (~244days) operation. Device now generating 8*1kW*244 = 1952 kWh p.a.

The production of 1952 kWh p.a. is based on the assumption that the weather is clear for the eight hours. This of course would not be the case, so the average output of the PV of 800 kWh can be divided by the assumed output 1952 kWh to produce a factor of 0.41. This summates to the weather being clear for 41% of the 244 8-hour days.

- The device is therefore on for 8*0.41 = 3.2h per day which equates to 3.2 kWh of generation.

From this, and assuming the maximum output from the generator occurs at midday, the PV generator profile (Figure 1) can be deduced to yield this 3.2 kWh of daily generation.

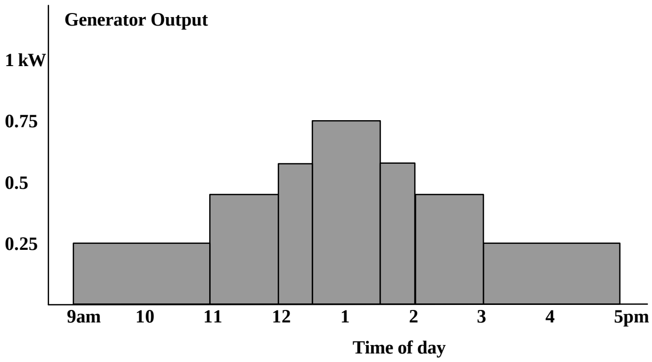

Figure 1: Typical PV generator profile

This Generator profile was then used to create the PV generator type for use in the "*Embedded generation for Debut*" program.

CHP Generator Profiles

Small-scale CHP systems, where waste heat from the electricity generation process is used to provide heating, are likely to be in the form of Stirling engines and fuel cells for use in individual dwellings. It is expected that the type of dwelling which will install these types of single phase generators will be larger houses, probably over 40 years old, which require new heating systems. The occupants may find it preferable to install a CHP type generator as the heating system for the house.

Typical ratings for these type of small scale generators are 3 kW with a power factor of between 0.8 and 0.9. A 3kW unit at 0.85 p.f. is considered for this study.

The devices, when used in these types of scheme, are either full-on or off. A typical profile for a 3kW CHP generator output on a weekday in March is illustrated below (Figure 2).

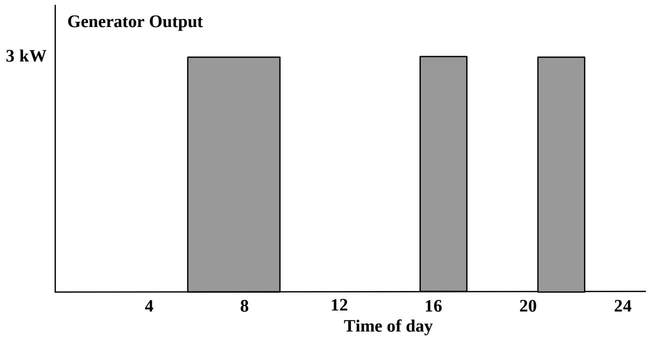

Figure 2: Typical CHP generator profile (March weekday)

Graphs from CHP generator studies carried out at EA Technology were obtained in order for true CHP generator scheme load profiles to be modelled. Data for a typical March weekday consumer load is illustrated below (Figure 3). The CHP load type was generated from these profiles.

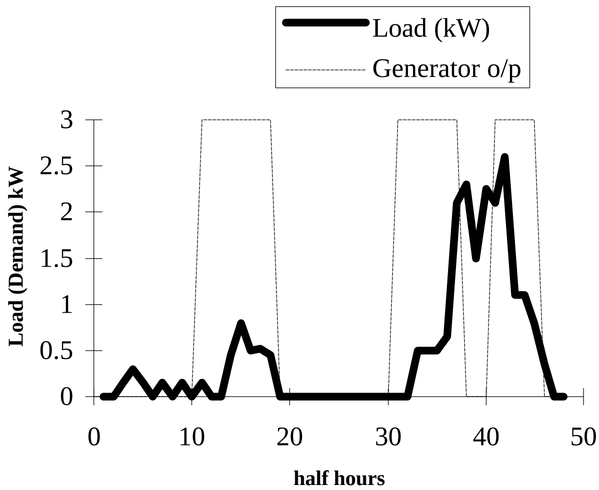

Figure 3: 3kWe CHP generator output & consumer load (March weekday)

CONCENTRATION OF GENERATORS

PV studies were carried out for a market penetration up to 100% on one network branch, to consider the effects of new housing estates appearing on the network. For a CHP generator, network voltage levels and currents for a market penetration of up to 10% were analysed.

Scenario 1 (PV schemes)

For this scenario, the generators were added to one branch of the network in stages: 0% (no generators), 50% and 100%. The generators were spread over one branch only to represent the fashion in which the generators are likely to be installed.

Scenario 2 (CHP schemes)

For this scenario, the generators were added gradually between 0% (no generators) and 10%, the 10% representing 36 generators added for 360 consumers on the network. The generators were spread evenly over the network, and network phases, to represent the randomness that is likely to occur in the installation of the generator schemes.

IMPLICATIONS OF THE TECHNICAL STUDIES

Results were obtained for voltage profiles, current profiles and substation loading.

Load Flow Analysis (PV schemes)

The studies for Scenario 1 (modern housing estate) illustrated the network voltage drops before and after the PV generation schemes were added.

The results for substation loading showed the feeder load with no generation connected, with 50% and with 100% of the consumers having PV generators connected. The feeder current was plotted at each half hour over a 24 hour period.

The network voltage change studies enabled the voltages at each node on the network to be compared before and after generation was added. The average phase node voltages for two nodes on the network were plotted. The observed maximum and minimum phase voltages were also derived.

Load Flow Analysis (CHP schemes)

The studies for Scenario 2 (established residential area network) showed the network voltage drops before and after the CHP generators were added. Graphs were created showing the substation load with no generation connected and with 10% of the consumers having CHP load profiles and generators connected. The substation current was plotted at each half hour over a 24 hour period. The graph shows the peak substation currents that occur with varying degrees of generation connection, from 0 to 10%.

The network voltage change studies carried out, enable the voltages at each node on the network to be compared before and after generation was added. Minimum and maximum nodal voltages were plotted for 4 nodes on the network.

DEBUT SOFTWARE FOR THE STUDIES

The network studies were carried out using EA Technology's *WinDebut* software and the "*Embedded generation for Debut*" program. *WinDebut* is an updated Windows version of the EA Technology produced LV network design software, *Debut* [3]. The "*Embedded generation for Debut*" program is a software tool which can be used to examine the effects of adding embedded generation to *Debut*-designed LV networks.

The *WinDebut* software was used to design the two scenario networks and to produce consumer demand curves which mirrored those which occur with the embedded generation schemes. The "*Embedded generation for Debut*" program enabled new generator profiles to be input. These were then used when adding generation to the networks produced in *WinDebut*. The output files produced enabled the network characteristics such as feeder voltages and currents, before and after generation is added, to be compared.

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