An Intelligent Fuse-box for use with Renewable Energy Sources integrated within a Domestic Environment

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Abstract—**This paper outlines a proposal for an intelligent fuse-box that can replace existing fuse-boxes in a domestic context such that a number of renewable energy sources can easily be integrated into the domestic power supply network, without the necessity for complex islanding and network protection. The approach allows intelligent control of both the generation of power and its supply to single or groups of electrical appliances. Energy storage can be implemented in such a scheme to even out the power supplied and simplify the control scheme required, and environmental monitoring and load analysis can help in automatically controlling the supply and demand profiles for optimum electrical and economic efficiency. Simulations of typical scenarios are carried out to illustrate the concept in operation.**

Index Terms—**Renewable Energy Sources, Power Electronics, Efficiency, Domestic Energy**

I. INTRODUCTION

One of the biggest problems with the connection to the public utility of renewable energy generators at any level is the requirement to ensure adequate power quality, reliability and safety of that generator. One significant problem is that of 'islanding' where the generator and load circuit becomes detached from the public utility, which can lead to significant safety issues. This problem has been discussed extensively in the literature by Chan, et al. [1], Chan, et al. [2], Lasseter and Piagi [3], Munro, et al. [4], Redfern, et al. [5], Redfern, et al. [6], Salman [7] and Usta, et al. [8].

Existing approaches have tended to concentrate on bi-directional power flow, where the generators have the ability to supply power back to the utility in the event of a power surplus. While this may well be feasible in larger scale applications, in a current domestic context the amount of energy generated by a small number of renewable generators will not cover 100% of the load requirements over a complete daily cycle. An alternative method is to treat the power flow as purely uni-directional into the load, and use a different approach to managing the supply of energy to the various loads.

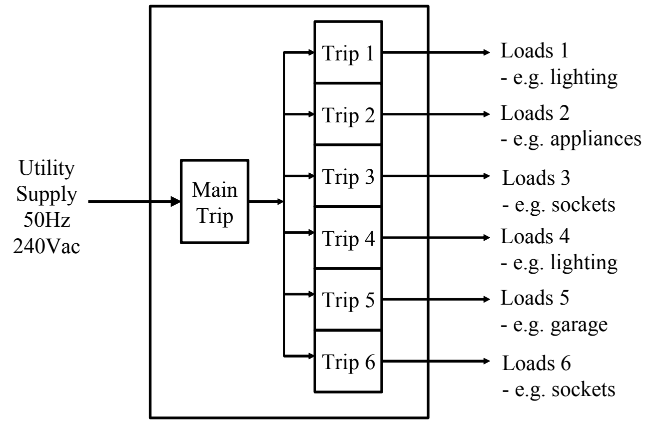

Figure 1: Typical UK domestic electrical fuse-box layout.

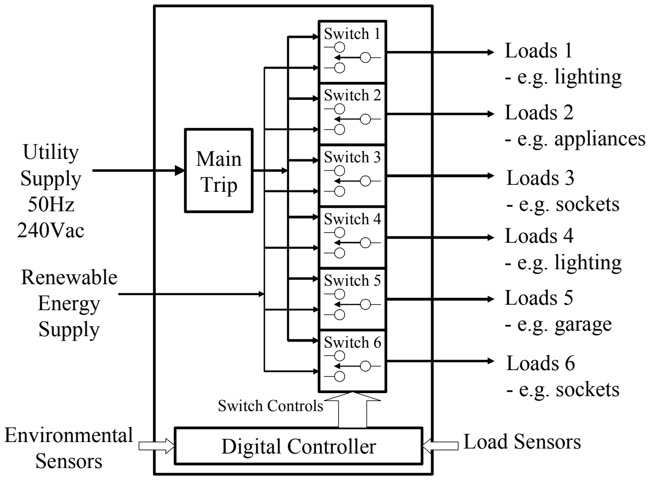

Figure 2: Proposed New domestic fuse-box layout.

Figure 1 shows an example of a typical domestic electrical fusebox and how the electricity supplied via the public utility is separated into a number of sub-networks supplying groups of appliances. The fuse-box in a modern built home (within the last 10 years or so) in the United Kingdom will generally have a set of resetable trip switches for each of the sub-networks, and an overall trip switch for the main supply. These trip switches have two purposes, one is to isolate part or all of the network in the house for maintenance to be carried out, and to automatically switch out part or all of the network in the event of an over-current fault.

With the increased interest in integrating small renewable and high efficiency energy generators into a domestic environment, a significant problem is apparent for the electricity supply companies, how to deal with potentially millions of un-regulated and un-controlled micro-generators appearing and disappearing from the network. Much work has been done on the development of these energy sources from a technical point of view including Abouzhar I. [9], Ghorashi, et al. [10], Chen and Spooner [11], De Broe, et al. [12], Rogers [13], Rogers [14], Roaf and Fuentes [15], Posnansky, et al. [16], Rogers [17], Cross [18], Carno, et al. [19] and Doble and Abu-Ebid [20]. Similarly, there has been much investigation into the issues with connecting generators to the public utility at a variety of levels, with regard to power quality and safety in particular such as Heggie and Yip [21], Thomas [22], Salman [23], Rogers [24], O'Kane and Fox [25], Salman [7], Jenkins and Strbac [26], Redfern, et al. [27], Redfern, et al. [28], Kirawanich and O'Connel [29], Vasanasong and Spooner [30], Vasanasong and Spooner [31], Redfern, et al. [32] and Carno, et al. [19].

In most of these cases, the emphasis has been on not only supplying power to the load, but also integrating directly with the utility. In this paper a different approach is proposed. If the simple fuse-box currently used is replaced by a digitally controlled fuse-box, with switches that can control the power to the load being from either the external utility or from an internally generated supply, then some of the significant problems can be addressed. The alternative strategy is shown in figure 2.

II. PROPOSED FUSE BOX STRUCTURE

The new fuse box structure has a number of switches for each set of loads. Each load circuit has a nominal rating, but the current flows are also monitored so that the digital controller knows and can predict the actual usage required. The controller has inputs for multiple sensors such as temperature, sunshine (irradiance) and wind speed, so that the potential output from generators can also be predicted. If an energy storage element such as a battery bank, flywheel, or other storage mechanism is used, then the state-of-charge can also be used to allow intelligent decisions to be made about the switching of certain circuits over to the internal energy sources. Each load will have a tolerance to switching over from one energy source to the other. For example, lighting will flash briefly for significant switching times, but this may not be apparent of the switching time is only a few milli-seconds. Switching over a refrigerator may not have a discernable impact for switching times of several minutes. In contrast, electrical appliances that rely on a reliable electricity source, such as televisions or computers need to have some kind of protection or UPS in place if the switching is to be incorporated.

III. RENEWABLE POWER CONNECTION STRATEGY

On of the important issues to be resolved in this scheme is how to integrate renewable generators in such a way that they can be intelligently applied to the loads. There are generally three main types of generator that could be easily applied in this context, photovoltaic, wind turbine and CHP (combined heat and power). Photovoltaic cells generate DC output, wind turbines can generate DC or AC, and the AC could be variable voltage and frequency, while the CHP generally produces an AC output. Obviously there are both conversion and synchronization problems to be resolved. One approach is to use an intermediate DC energy storage medium, such as a battery, to store the energy generated by all the individual sources, and then have a single inverter that is synchronized to the mains. Even if there is no mains supply present (due to a fault perhaps), the intelligent fusebox can generate a default supply at the correct frequency and voltage. As the connection to the utility is uni-directional, there is not the conventional difficulty of assessing whether the generator or the utility has failed. Another approach is to have a number of separate converters and inverters to provide an array of internal energy sources that can simply be plugged into a bus bar to be used as required. As the supply synchronization is controlled centrally by the fuse-box then each power module can be synchronized on connection to the bus.

IV. OPERATION OF INTELLIGENT FUSEBOX

The way that the fuse-box operates depends on a number of factors. By programming into the fusebox the required operational characteristics, then the control of the switches can be configured. If the operation is considered to be in the context of a consistent and reliable utility supply (nominal operation), then the controller simply has to monitor the energy generated by the renewable sources, and also the load requirements (in conjunction with a history of profiles of usage in load and environmental contexts) to switch over a number of the switches to the renewable generators if there is enough power to run the loads. The loads can be configured such that perhaps the most tolerant of a variable supply are switched over first, such as the lighting circuits.

The use of history on the usage of the loads depending on time of day, season, weather and occupancy profiles, means that an accurate prediction of the likely load usage can be built up to maximize the efficiency of the fuse-box and also minimize the number of switching operations.

V. SIMULATION OF THE INTELLIGENT FUSE-BOX (IFB)

In order to test the performance of the IFB under realistic load conditions a simulator of the system was created. The simulator consists of two main parts, the layout editor where the fusebox is configured, loads added and generation included, and the simulation engine that calculates the load profiles, and the resulting system performance.The basic layout editor is shown in figure 3, with an eight switch IFB, connected to a set of sample domestic loads. The system under test includes a battery storage element of 10kWh, a small wind turbine, and a set of solar panels (10m^2).

The wind turbine model uses the basic wind-speed power generation equation given by (1).

$$P_w = 0.5 C_p \rho\ V^3 A \tag{1}$$

The generator can be configured with constant and variable power, or by specifying the characteristics of the wind turbine. In this instance C_p, the power coefficient, is 0.59, ρ, the air density, is 1 and A, the area of the blades, 5m^2. The torque applied to the shaft of the turbine is this force multiplied by the distance of the center of lift from the shaft (d). Thus the torque applied to the shaft can be calculated using (2).

$$T_{gen} = 0.5 C_p \rho\ V^2 A d \tag{2}$$

Where T_{gen} is the generated Torque and d is the distance to the center of lift from the shaft. Thus far the turbine power coefficient (C_p) has been assumed to be constant, but in practice this depends on both the wind and blade tip speeds. Usually the turbine power coefficient is expressed with respect to the tip speed ratio (λ) that is defined in (3).

$$\lambda = \frac{w}{v} \tag{3}$$

Where w is the tip speed and v is the wind speed. The turbine power coefficient can then be expressed with respect to the tip speed ratio as shown in an example in figure 3(a). The resulting simulated wind turbine power profile for a typical 24 hour period based on measured wind data is given in figure 3(b).

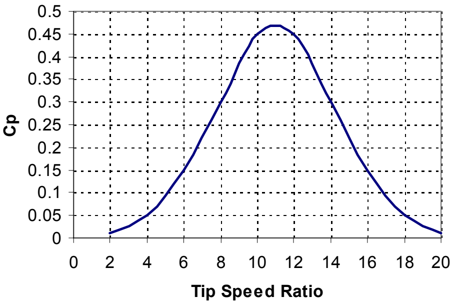

Figure 3(a): Cp versus Tip Speed Ratio

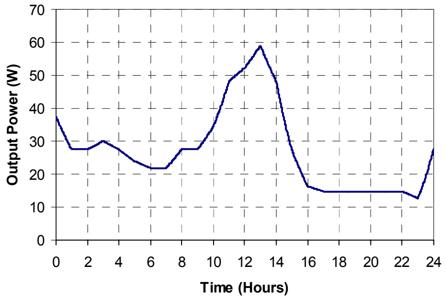

Figure 3(b): Wind Turbine Output power over 24 hour cycle

Using this function, the turbine power coefficient can be made more realistic across the dynamic range of the turbine. The generated torque (T_{gen}) can be applied to the output mechanical pin, that is defined using the rotational mechanical units that are analogous to voltage and current in the electrical domain, thus torque is the through variable (current) and rotational speed is the across variable (voltage). Using this approach, the mechanical model of the turbine can be expressed using equivalent elements in an electrical circuit simulator (Spice, VHDL-AMS, Verilog-AMS). The real turbine also must include inertia (j) and damping (d), and this can be implemented using the expression given in (4), where the torque applied to the shaft is calculated taking the inertia and damping into account.

$$T_{shaft} = T_{gen} - \frac{d}{dt}(jw) - dw \tag{4}$$

The photovoltaic model first calculates the power incident on the individual solar panels by multiplying the area of each panel by the irradiance. The panel efficiency is then estimated based on the maximum efficiency parameter *eff* and using an empirical parameter k that modifies the efficiency depending on the power incident to the panel. This is non-linear relationship as described in (5). In practice this also depends on the panel and ambient temperature, but this has been neglected in this model for simplicity. The power output from the panel is also limited to the maximum rated power output value with the parameter *pmax* and then scaled up to the number of panels in the array with the parameter n.

$$\eta = \eta_{\max}\left(1 - e^{-kp}\right) \tag{5}$$

Where η is the estimated efficiency, η_{max} is the maximum efficiency (0.4) , k is the empirical efficiency variation parameter (0.2) and p is the ratio of the input and rated powers (rated power=1kW). In this case the total area of panels was set to 10m^2. The output from the solar panel configuration and the irradiance are shown in figure 4.

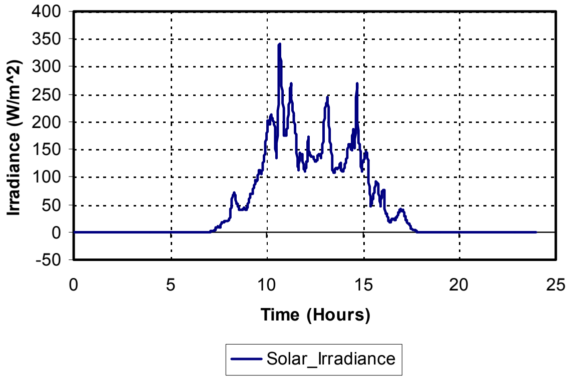

Figure 4(a): Measured Irradiance over 24 Hour period

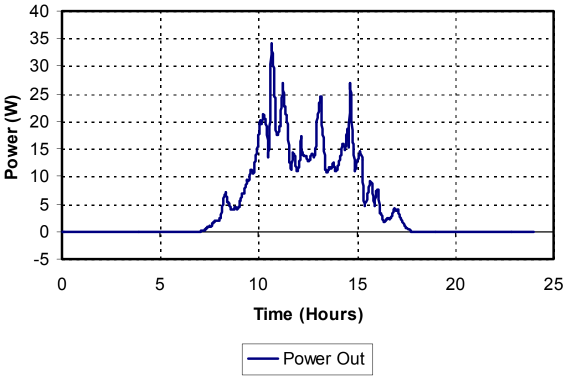

Figure 4(b): Solar Power Output from PV array

VI. Energy Balance System Simulation

In order to demonstrate the applicability and effectiveness of the system models presented in this paper a basic PV-Wind hybrid system for a domestic load was tested. In this model the PV array model was used in conjunction with a simple wind turbine model to estimate the potential power that could be obtained from these two sources. Sample domestic loading data for a single domestic dwelling was used as a test load, and a generic storage element was included to simulate the effect of having storage in the system, without the necessity of specifying the details of the storage method precisely (i.e. battery, flywheel, or pumped storage). The schematic of this system model is given in figure 5(a).

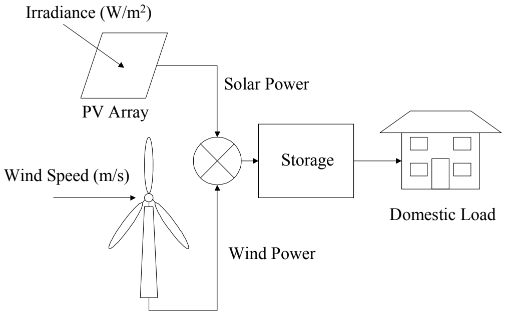

Figure 5(a): PV-Wind Hybrid System Simulation Model

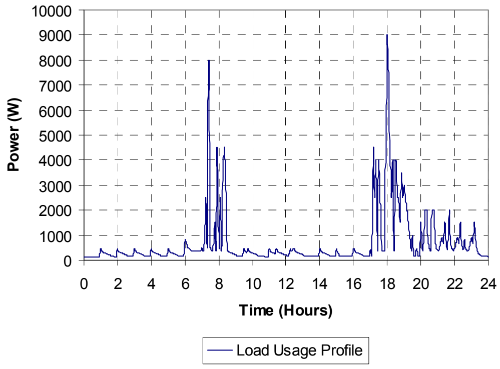

Figure 5(b): Domestic Load Usage Profile over 24-hour cycle

The test data for the solar radiation was obtained from the Southampton Test and Reference Facility (STaR), University of Southampton, the wind data was obtained from the Martin Centre, University of Cambridge and using a typical domestic load (The author's family home). Using a simple model with a single domestic load and a 2400Wh storage facility, a 5m^2 wind turbine and 20, 100W, 1m^2 Solar Panels, a system simulation was carried out the estimate the energy balance of this type of system over a sample 24 hour period. The irradiance and wind speed used were the results shown previously in this paper. The domestic load requirements over the same 24-hour cycle are given in figure 5(b).

Each switch in the modified fuse-box within the simulator was configured to be either renewable active, meaning that the loads connected to that switch could be switched over to the alternative source, or renewable inactive, where the loads were always connected to the utility. In general for this feasibility study, sensitive loads such as computers would be always connected to the utility. The simulator also includes economic pricing data for the cost of electricity from the utility with peak and off-peak costs. A comparison was made between the costs with and without the intelligent control of the renewable energy sources, and the resulting savings for a typical day were 20%. In order to graphically measure the effect of different loading and generation strategies a power manager simulator was developed as shown in figure 6. Figure 6(a) shows the demand profile editor, where loads can be added to individual fuses (ring mains) and the integrated renewable energy sources connected to the generation side.

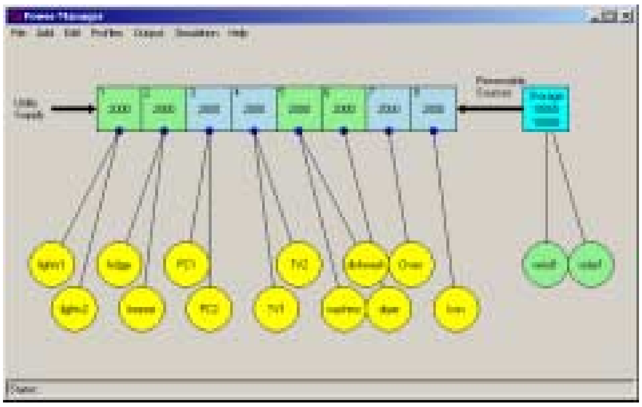

Figure 6(a): Power Manager Layout

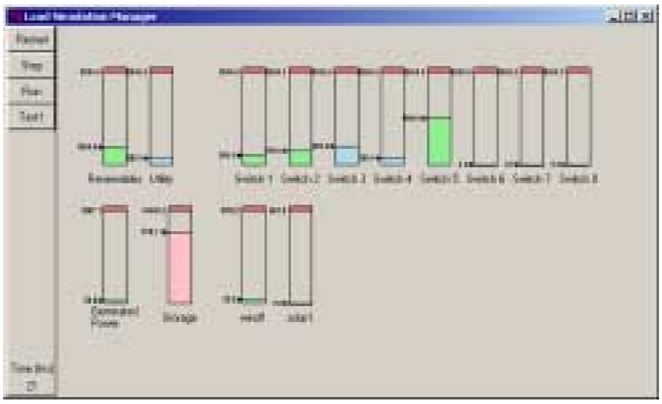

Figure 6(b): Power Manager Simulation Window

The results of simulating the configuration in figure 6 show how the prevailing weather conditions affect the amount of renewable energy that can be practically switched to individual appliances, how different storage strategies can be used to ensure maximum benefit from the renewable energy sources and how the system can be made most cost effective. Form the siomulation, an estimate of the energy input and output was obtained and is given in figure 7(a). This demonstrates how the load requirement outstrips the potential generated power using only solar and wind power in this location.

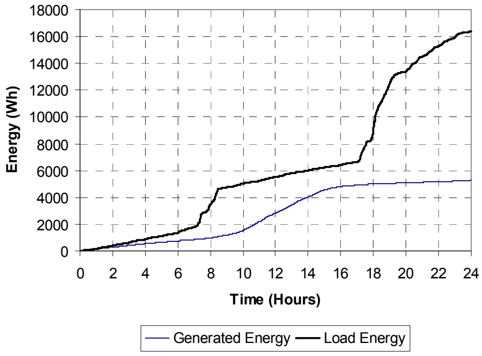

Figure 7(a): Generated and Load Energy Comparison

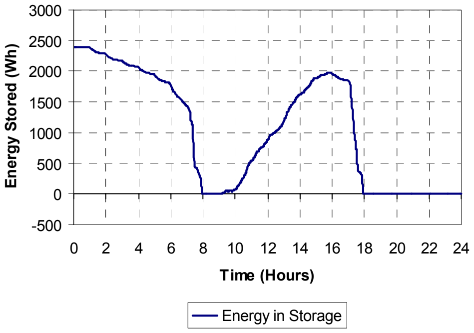

Figure 7(b): Stored Energy Profile

With an energy storage element capacity of 2400Wh, it is clear from the graph of the stored energy given in figure 7(b) that this size of energy storage is insufficient to cope with this load usage profile and the current generator configuration. This energy storage figure was based on two 100Ah, 12Vdc batteries of the type commonly used for PV energy storage. Figure 7(b) demonstrates that from a fully charged storage element, during the two peak periods (in the morning and evening), the energy requirements of the load not only take all of the energy produced by the generators, but also that the stored energy is depleted to zero. With this configuration it would necessary for the system to draw power from the utility to 'top up' the available energy from the renewable sources. Using this high level system model, it is then possible to experiment with the choice and size of generators, storage elements and load profiles to estimate the best mix to support the required load profiles. For example, by increasing the area of solar panels to 100m^2 and the storage to 9600Wh (8 batteries of 1200Wh each), the resulting energy stored over the same 24 hour period does not fall to zero and is just able to cope with the requirements of a typical domestic demand profile.

VII. CONCLUSIONS

A new approach to the management and control of renewable energy sources in a domestic context is presented. A prototype model demonstrates the operation of the system, and results are presented that show the potentially significant savings that may result from this scheme. The simulation models developed allow a rapid specification and development of system configurations that can be tested with real demand profiles and weather data taken from local test stations. The controller can be tailored to provide the most economic or the most environmentally friendly generation and power configuration – both of which can be tested using the power manager simulator.

Ongoing research funded by EPSRC is developing a test facility in Southampton that will integrate a prototype monitoring and power management system, complete with integrated renewable energy sources and storage to test the simulation predictions in a practical domestic situation. By early 2005 the authors will present preliminary results taken from this facility.

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