Proposed Components for the Design of a Smart Nano-Grid for a Domestic Electrical System that Operates at Below 50V DC

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***Abstract*-- The need and advantages of the use of direct current voltage for domestic usage has been presented, however at a very-low dc voltage, the system suffers from voltage loss constraints and higher than usual load currents. Some of the parameters that cause load-induced voltage drops and the resultant ramifications to the usability of the electric network are discussed. The system needs a dynamic mechanism to control the voltage at any node each and every time a new load is connected or a load is removed from the system. This paper seeks to use smart house technology in the form of a smart grid, intelligent appliances and interactive power nodes to circumvent and mitigate these problems. The requirements and possible components that the smart grid will need to provide, are set forth. The use of power line communications over the DC electricity mains using CAN-bus or LIN-bus protocols is discussed.**

***Index Terms*— alternating current voltage, automatic voltage control, direct current voltage, dynamic control mechanism, intelligent appliances, nanogrid, power line communications, smart grids, smart house technology, voltage drop,**

I. DEFINITIONS

Node; The power socket in the home into which the appliance is plugged, is called a node

Nanogrid; For the purposes of this paper a nanogrid Is the name given to an electrical mains system for a single house, as opposed to a micro-grid which is usually for a power supply system for multiple buildings.

A Smart Nanogrid; A nanogrid that uses embedded electronics and computer controls to autonomously measure every component connected to the grid and uses dynamic control to make decisions based on pre-programmed conditions and interacts with the home owners actions.

II. INTRODUCTION

A. *Why use Direct Current voltage?*

In recent years there has been growing interest in the use of DC in the home, partly because many modern home appliances use DC voltage and most renewable energy sources generate DC power. By using DC voltage as the mains electricity system, the multiple stage energy conversions associated with a conventional AC system, which is fed from DC microgenerators, are eliminated. This includes the expensive inverter which is always needed when DC microgenerators feed into an AC electrical system. Therefore by exchanging the conventional AC-to-DC converters with integrated circuit DC-to-DC converters there should be the added benefit of a consequential saving in energy conversion losses, a reduction in the use of raw materials in their manufacture and therefore a reduction in the carbon footprint of the home. Different design implementations/scenarios have been investigated [1] from which it has been shown that an extra low voltage home of below 50V DC is possible. However there are constraints associated with voltage drops along the cables that reduce the operability of the home. To overcome these problems a smart grid as part of an integrated smart house in envisioned.

The DC house is not an alternative to a conventional AC house, and cannot at this time supersede it. However what the DC house can do, is help to bring a degree of energy independence with security, [1, Section 1.3.0] when implemented in the form of a hybrid AC/DC house [1, Chapter 5]. And for the millions of households in the developing world that are not connected to an electric grid, and who may have to wait a long time until this may be possible, the DC house can provide a standalone solution now, which will increase their standard of living now. The quicker electricity is available to a society the faster GDP will grow [2, 3].

III. EXAMPLE SYSTEM AND ITS EQUATIONS

A. *Introduction and Voltage Drops*

The decrease in voltage between two points in a transmission system is termed a voltage drop and is a measure of the efficiency of the transmission system. How much the voltage drops depends on the amount of current flowing in the conductor and its length, and is measured in millivolts per amp per metre (mV/A/m). In a conventional domestic AC supply, voltage drops associated with domestic appliances are by design usually insignificant and therefore do not adversely affect the voltage available to the appliances even when large powers are being drawn. However in a system operating at below 50 Volts, for a given load power rating, the current drawn will be far larger than that of a conventional 230 Volt AC system. Thus the I^2R losses are also larger, which causes a larger voltage drop for the same length of cable in the below 50 Volt system than that in the 230 Volts system. Besides the drawn current there are many system parameters that will affect the actual voltage along a cable.

B. System equations

The measured voltage at a given node along a cable is given as the system voltage minus voltage loss.

$$V_{nd} = V_{sys} - (V_{tab} * I * L) \tag{1}$$

Where

V_{nd}	The voltage at a given node (V)
V_{sys}	The system voltage (V)
V_{tab}	The tabulated voltage drop in millivolts per ampere per metre until a node (mV/A/m)
I	The current rating of the load at a node (A)
L	The length of the cable in metres from the voltage source to a node (m)

The tabulated voltage drop per ampere per meter, V_{tab} , is given in the tables of Appendix 4 of the British Standard 7671:2008 [4]. However the given value is only in the specific situation when the load current drawn equals the current carrying capacity of the cable, which itself differs according to the cross-sectional area of the cable. The cabling in the DC house is designed such that no single appliance will draw a current larger than the current capacity of the cable, and that the amount of appliances that can be attached to the cable should correlate to the number of nods on it. Therefore when a single appliance is connected, it will draw a current well below the carrying capacity of the cable and consequently the values given for V_{tab} will be too high for the calculations.

To calculate the actual voltage drop per ampere per metre (V_{cal}) when the loads connected to the cable draw a load current below the cable's full thermal current rating, a correction factor (C_t) will have to be applied. The equation for C_t is given in Appendix 4, Section 6.1 of the BS7671 and is shown in (2) below.

$$C_t = \frac{230 + t_p - \left(C_a^2 * C_g^2 - \frac{I_b^2}{I_t^2} \right)(t_p - 30)}{230 + t_p} \tag{2}$$

Where

C_t	Correction factor
t_p	Maximum permitted conductor operating temperature
I_b	Operating current of load and cable run
I_t	Tabulated maximum current carrying capacity of cable
C_a	Rating factor for an ambient temperature
C_g	Rating factor for grouping

From (3) V_{cal} can be shown as

$$V_{cal} = V_{tab} * C_t \tag{3}$$

V_{cal} is substituted for V_{tab} in (1) which now becomes (4)

$$V_{nd} = V_{sys} - (V_{cal} * I * L) \tag{4}$$

To calculate the actual operating temperature of the cable (5) is used. This equation is adapted from [5]

$$t_{op} = t_a + \frac{I_b^2}{I_{ta}^2}\left(t_p - t_{amp}\right) \tag{5}$$

Where

t_{op} (t_1)	Actual operating temperature for the cable
t_a	Actual ambient temperature
I_b	Current rating of appliance
I_{ta}	Actual tabulated current carrying capacity of the cable
t_p	Maximum permitted conductor operating temperature
t_{amb}	Rated ambient temperature

C. Consequences arising from the system equations

It can be seen from (2) that C_t is affected by the ratio of the square of the load current to the square of current capacity of the cable. With a 4mm^2 cable of 25A capacity, if the load current is very small at 0.01A, then the ratio I_b^2/I_t^2 becomes so small that it does not affect C_t. For values of less than 0.5A, C_t to four decimal places can only get as small as 0.8667, [1, Table A1-2 Appendix 1] which puts it in a range of $1 < C_t > 0.8667$. The other factor affecting C_t is temperature, however in (2) ambient temperature is taken as 30ºC. In reality rating factor for grouping of (2) as well as the physical installation of the cables and the changing ambient temperature, as can be seen in (5), also affect the conductivity of the cable. This in turn affects C_t and the voltage drop along the cable. In ordinary AC systems or in equivalent DC systems these changes may not adversely affect the actual voltage at a node. However in an extra low voltage system of below 50VDC, especially at 24VDC, these small changes have consequential affects on the node voltage. Thus although some of the factors affecting the voltage at a node are defined, actual length of cable from source to node and between each node may not be known, the changes in total load current and V_{cal} associated with the random introduction of another load anywhere onto the system and, the ambient and conductor temperature, are all system variables that change. (For a fuller discussion see [1, Chapter 3]). As such a dynamic control mechanism is needed to ensure the safe and correct operation of the system.

D. An example system specification

A proposed electrical system is a 24 VDC supply with a single 4mm^2 cable run of 20m. 24 Volts was chosen, as this is the voltage of the DC appliances that are commercially available, however various voltages were chosen by [1, Section 7.4.1] depending on the type of load. On this system there will be four nodes which will allow four appliances to operate at the same time. It will be assumed that the voltage tolerance of the appliance manufacturers is ± 5% of the system voltage which equates to 24V ± 1.2V. This value is chosen as it is the best practice value as given in Appendix 12 of British Standard 7671:2008. However in reality each appliance will have its own manufacturer's tolerance. The four appliances were chosen such that their combined drawn current will be more than the current carrying capacity of a 4mm^2 cable. It is also assumed that the actual length of cable from source to each node is known, something that in a real house will usually be unknown, and therefore will have to be taken into consideration by the control system. It is also assumed that the cable connecting the appliance to the node is insignificantly small for our calculations. However in reality it can be up to a few meters long and will have its own voltage drop characteristics.

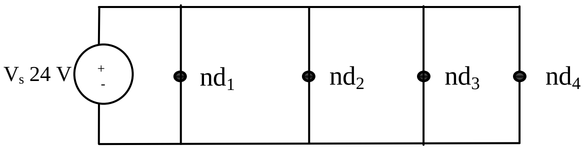

Fig 1. 24v DC example domestic electrical radial main

nd denotes node

Cable lengths:

V_s to nd$_1$ 5 meters
V_s to nd$_2$ 11 meters
V_s to nd$_3$ 15 meters
V_s to nd$_4$ 20 meters

TABLE 1

24 VOLT DC APPLIANCE CONFIGURATION EXAMPLE

Appliance	Connected to node	Appliance current (A)	Current drawn at node (A)
indelB Cruise 195 Fridge/freezer	1	1.38	1.38
Summit Kettle C1206	2	10.00	11.38
DC Airco 4400RM Air conditioner	3	12.50	23.88
Freeview receiver	4	2.00	25.88

E. Example calculations

Using the data from Table 1, the values from Appendix 4 [4] for a 4mm^2 cable and the above equations, Table 2 was derived. To understand how adding a new appliance will affect the ones already connected, a diagram for each equivalent circuit is set out below. The annotation used to describe the nodal voltages is v_{ab} , a being the number of the node and b indicating how many appliance are connected at that time.

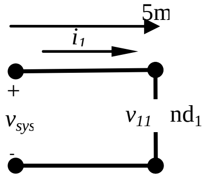

Fig.2a The equivalent circuit when the fridge freezer is connected to node 1

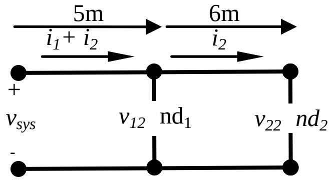

Fig.2b The equivalent circuit when kettle is added to node 2

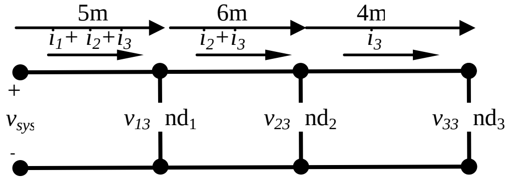

Fig.2c The equivalent circuit when the Air conditioner is added to node 3

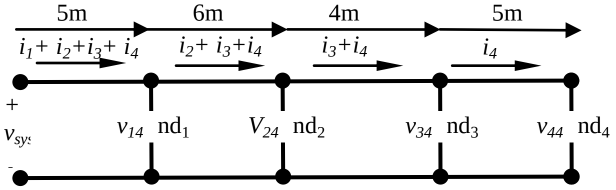

Fig.2d The equivalent circuit when all four appliances are connected

TABLE 2

CALCULATIONS USING AVAILABLE 24 VOLT APPLIANCES

No. of appliances attached	Nodal Current (A)	Ct	Vcal mV/A/m	Length between nodes (m)	Vnd (V)	% change	nodal voltage
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
1	1.38	0.8671	9.5378	5	23.93	0.27%	V11
2	11.38	0.8943	9.8372	5	23.44	2.33%	V12
2	10.00	0.8880	9.7680	6	22.85	4.77%	V22
3	23.88	0.9883	10.8715	5	22.70	5.41%	V13
3	22.50	0.9747	10.7213	6	21.25	11.44%	V23
3	12.50	0.9000	9.9000	4	20.76	13.50%	V33
4	**25.88**	**1.0096**	11.1051	5	22.56	5.99%	V14
4	24.50	0.9947	10.9419	6	20.95	12.69%	V24
4	14.50	0.9115	10.0267	4	20.37	15.11%	V34
4	2.00	0.8675	9.5427	5	**20.28**	15.51%	V44

What is happening to the system?

The appliances were connected to the system in the order they appear in Table 1. When the first appliance is connected to node 1 the system equates to Fig 2a. It causes a voltage drop of only 0.07V at node 1. When the second appliance is added at node 2, the voltage at node 1 changes as the current drawn at node 1 will be the combination of both currents, while the current drawn at node 2 will only be that of appliance 2 (Fig 2b). Adding the second appliance further reduces the voltage at node 1 by 0.49 V to 23.44V and the voltage at node 2 becomes 22.85V. Similarly by the time all four appliances are connected using this configuration, (Fig 2d) the voltage at node 1 is reduced to 22.56 V and at node 4 to 20.28V.

No. of appliances attached	Nodal Current	Ct	Vtab mV/A/m	Length between nodes (m)	Vnd (V)	% change	nodal voltage
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
1	0.69	0.8668	11	5	47.97	0.07%	V1
2	5.69	0.8736	11	5	47.73	0.57%	V12
2	5.00	0.8720	11	6	47.44	1.17%	V2
3	11.94	0.8971	11	5	47.41	1.23%	V13
3	11.25	0.8937	11	6	46.75	2.61%	V23
3	6.25	0.8750	11	4	46.51	3.11%	V3
4	**12.94**	**0.9024**	11	5	47.36	1.34%	V14
4	12.25	0.8987	11	6	46.63	2.85%	V24
4	7.25	0.8779	11	4	46.35	3.44%	V34
4	1.00	0.8669	11	5	**46.30**	3.53%	V4

This 24V system can quickly have integrity problems if all appliances are connected at the same time. The first problem being that the current rating for a 4mm^2 cable is 25A, which becomes exceeded with the connection of the fourth appliance. Good practice as described in Appendix 12 in [4] is a 5% voltage drop. Under normal operating conditions the fridge freezer connected to node 1 will undergo a change in the voltage available to it, from 23.93V to 22.56V, which is a maximum voltage drop of 6%. As for the Freeview receiver when it is attached to node 4 the voltage available to it will only be 20.28V which is only 84.5% of nominal voltage. In reality the safe operation of the appliances in an electrical system that has changing voltage, will depend on the operating voltage range set by the appliance manufacturer, and could in theory be more than -16% of nominal voltage. However it would not be good design optimisation to make a product with such a large voltage range. What also has to be taken into consideration is that with four nodes and four appliances there are sixteen ways that the appliances could be configured in the system. Therefore for 100% reliability, all appliances would have to be designed for a worst case scenario that would allow safe operation with a 16% voltage drop. Note; (1) the 16% voltage drop is only for this particular configuration. Each configuration of appliances will have its own voltage drop characteristics. (2) These calculations are for ordinary conventional appliances that do not have and smart capabilities to adjust their current intake in proportion to delivered voltage.

Therefore in this case, as there are appliances with a relative high individual current of over 10A, a nominal voltage of 24V will be too low. As explained the reason for choosing 24V was purely due to the availability of real appliances, however this is not stated as being the optimum voltage for domestic usage. Therefore now that the limitations to the usability of the system have been show, the voltage must be increased. In keeping with the design criteria for the DC house, that it should be able to operate at below 50V DC and for simplicity, the calculations were carried out using fictional 48V appliances. This was done by halving the current of the real 24V appliances. What emerges is by doubling the voltage and halving the current the system integrity in enhanced almost fourfold (compare column 7 in Tables 2 and 3).

TABLE 3
CALCULATIONS USING PROPOSED 48 VOLT APPLIANCES

In a real domestic situation, for many of the nodes there will be a random choice of appliances that will be connected to them. With each new added load the voltage at the node as well as all other nodes further along the cable will be changed. Also there will be many such mains cables throughout the house all connected to a central multiplexer board which is fed from a voltage controller connected to the electrical energy source. The extra low DC voltage home is a complex and dynamic environment. Therefore when someone comes to attach a device to the system, how do they know that it will operate safely, that they will not trip a circuit breaker, blow the fuse of or some electronics in, the actual appliance, or impede the safe operation of an existing operational appliance?

F. Solution Requirements

What is needed is a solution that can provide some way of knowing what the status of an individual node is and what affect attaching a new load will have on the whole system. It has to be able to identify the characteristics of all loads and provide a real time active control mechanism that maintains the correct operational voltage at each node. The solution to maintaining the electrical integrity of the system can best be provided by smart grid technology.

The solution provided by smart grid technology can be transposed to be used to control a DC house but with some added features. In the specification for the DC house it is presumed that the power supplied is enough to provide peak power for the whole house but not enough to allow any amount of loads on a given cable. However in reality this may not be so. Traditionally smart grids deal with the supply side of the distribution network to facilitate the correct balancing of supply to demand. However in the DC house the control mechanism will need to also control the demand side, such that at any given node in the system, demand will not be able to be greater than supply this is a balancing of demand to provide a security of supply.

IV. COMPONENTS NEEDED FOR THE SMART GRID IMPLEMENTATION

A. The whole system

The proposed smart electrical system will have three elements, the intelligent appliances, the interactive nodes and the computerised control mechanism which must be able to communicate with each other.

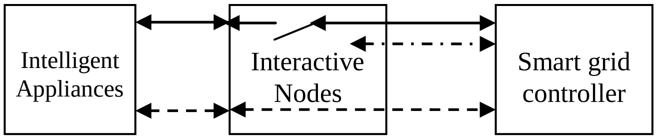

Fig 3 diagram of the whole system

Electrical power pathway ⟷
Data communication pathway ⇠⇢
System parameters measurement pathway ⇠·⇢

When an appliance is connected to the node, the switch on the electrical pathway will remain in the open position. The controller will detect that an appliance had been connected and it will send a signal through the communication channel requesting its identification data. If the controller assesses that the appliance can work properly at that node without adverse affects on any other nodes it sends a signal to close the switch and allows the appliance to operate.

B. The loads – Intelligent Appliances

Each DC appliance will need an electronic identifier which will contain its identifier parameters and have a communications channel to pass on this data to the system controller. Besides its basic voltage and current characteristics, there will be many parameters that the appliance manufacturer will want to provide for both its' safe operation and dynamic control. At this time the use of ZigBee specification hardware [6] is a tested method to provide this type of intelligence to the appliances.

At this time in an ordinary AC 230V house the mode of operation is either on, power flows, or off, no power. However in the DC house it is possible that at times of low power generation, circuit overload, or if it is running on emergency generation, partial power may be lost to the system. In such a scenario, decisions have to be made as to which appliances should have priority to use the available power. Within a conventional home system, the homeowner would have to decide on which appliances to give priority and go around the house and physically unplug those that are of low priority. However with smart control of the system this can be done automatically using a hierarchical identifier. Such an identifier puts each appliance in order of criticality to the homeowner which will be represented by a numbering system. For example general category of emergency lighting may be assigned a number 1, loads like the internet/telephony 2, refrigerator/freezer 3, other lighting 4 etc. then within each category there will be subcategories depending on importance. This hierarchical identifier should be part of an international agreed numbering system (ISO), perhaps in bands, but with the ability of additional control by the homeowner.

C. The nodes

In most conventional AC home gadgetry there is the requirement for AC to DC conversion and a step-down transformer. These transformers have an associated carbon footprint, as well as using up energy in operation, which can be detected by the heat they give off. In the DC home the DC to DC converter function will be removed from the appliance and placed in the nodes. It has been shown that there are up to 25 gadgets on average (in 2002) per home. [7, page 7] Therefore by taking this function out of the appliance there is the general reduction in the carbon footprint of the appliance as well as a reduction in the amount of DC converters used in the home.

The nodes therefore move from being in passive mode as they are in a conventional AC system to being in active mode in the DC system. They incorporate DC to DC converters, measurement electronics as well as the three distinct pathways/channels mentioned above. The DC to DC converters must be isolated from the electrical mains so long as there is no current flowing to an appliance otherwise energy will leak away all the time. Real time measurement of the relevant system parameters is carried out by an embedded module in the node.

D. The control mechanism

The control mechanism has to receive on the demand side, data from the loads and from the electronic module in the nodes, and on the supply side from the voltage regulation system. It has to provide active and intelligent control of power flows to each node on each cable. A standard dashboard type interface much similar to that provided for a national smart grid control system will be needed.

In times of emergency when supply is reduced a priority powering down protocol must be enforced. This will see power to the least important nodes being cut first with a gradual withholding of energy to the less critical nodes, balancing the system so that the most critical nodes being given priority and only being powered down last, the protocol prioritising according to the hierarchical identifier number of each load.

E. Mechanism for operation of an intelligent appliance

a) When a load is connected to a node, the mains electricity switch remains open while the communications channel is closed.
b) A signal is sent to the appliance to read its parameters
c) A decision is made based on measurements of all the other system parameters if it is safe to allow this appliance connectivity.
d) If yes, the electrical pathway is opened and the device goes operational.
e) If no, the electrical connectivity is denied by continuing to keep the electrical switch open. To operate the appliance another node must be provided.

f) On removal of the load the electrical pathway switch should automatically open again.

V. SERVICES THE SMART GRID CONTROLLER HAS TO PROVIDE

a) First and foremost is to make sure that the correct voltage is supplied to a node on request. To do this a calculation of the power drawn at all the other nodes on the cable will have to be continually monitored. For appliances that draw a variable current, like those that have variable speed, light intensity or temperature control, continual measurements will need to be taken to insure the safe operation for themselves and any other appliances connected to the same cable.

b) If the homeowner plugs in an additional load to a cable that will overload the cables' current capacity or due to voltage drop the system cannot provide the correct voltage at that particular node, the control system must not only disallow electrical connectivity but also indicate to the homeowner which alternative nodes are available. (In the DC smart house this could be via, a visual indicator, a sound/bleep indicator, a voice command from the smart house control system, via a text to mobile phone, or via a computer terminal)

c) It also has to act as a smart circuit breaker to stop the total load current not exceeding the current capacity of the cable.

d) It has to be able to close down power to a node when a load is operating outside of the manufacturers safe operating tolerances. If this is due to the system, for example reduced power supply, it must provide the home owner with a signal that this has happened and provide an alternative node to which the load can be safely connected. If the load has malfunctioned, for example a light bulb blows, the controller must cut power to that node and be able to send a signal to the home owner about the problem. It can keep the loads' identifier information in a list of faulty equipments to stop someone inadvertently connecting a faulty load to a node, but with a diagnostic test that shows that the appliance is now safe it will allow power to go to load.

e) Like any conventional smart grid system the controller should have the ability to balance the supply by switching to backup/ auxiliary power supply when primary supply is off or reduced. For example switch over from solar supply in the evening to the night time supply and switch back again in the morning.

f) When the supply cannot meet the demand action has to be taken to try where possible to keep operational as many nodes as possible. Using the hierarchical identifier, nodes with low priority are safely powered down with power being sent to the most critical nodes, and if this is not possible the homeowner is given a message which node to connect the critical loads to.

g) To save energy when unnecessary power is being drawn, the controller should close down the node. For example when a battery operated appliance is being charged once it is fully charged power is cut to that node.

h) In case of malfunction in the control system an easy override/ manual control mechanism must be provided. This should allow critical nodes to operate in the conventional way.

i) It is envisioned that the communication system used between the controller and the loads will be of very low power, a power very much smaller than that used in conventional standby power modes, in the milli Watt range. Therefore instead of disconnecting a load from a node a standby button could be used that will close the electrical pathway down while keeping the very low power communication pathway open. To power up the appliance, the homeowner needs only to press a standby button and the controller will turn on the appliance.

j) Providing feedback to homeowners about energy usage influences the way energy is consumed and makes them more conscious of wastages. This can be provided from the data collected by the control system.

k) If the house is connected to the grid the control mechanism should incorporate smart metering.

VI. THE COMMUNICATIONS SYSTEM

A. Communications over electrical mains cables

The electrical and communications pathways have to be implemented with copper cables. There are two possible scenarios, either a retrofit to an existing house or as part of a new-build house. It has been shown [1 section 3.6.2] that for an extra low voltage mains at below 50V, a 4 mm^2 cable will be needed. This is larger than conventional AC cables which are usually 2.5 mm^2 and therefore even in existing houses a new set of cable will have to be installed. Conventionally the only option that would allow communications without data loss problems would have been to use two separate sets of cables, one for the electricity and one for communications. However today there is the option of using one set of cables by creating a Power Line Communications Network (PLCN).

Digital communications over AC and DC power lines is inherently fraught with data loss problems [8, 9], which will have to be overcome in the DC house. However in recent years much work has been carried out with communications over the power lines in vehicles, including the availability of off the shelf hardware. For PLCN in vehicles there are two International Standards, ISO 11898 for high speed communications and ISO 11519-2 for low speed communications over a Controlled Area Network (CAN-Bus). There is also the Local Interconnect Network (LIN-Bus). At this time there are DC transceivers that simulate these protocols to mitigate power line communication problems.

Therefore the option of using one set of cables in the DC house for both power and communications is feasible. As the electrical system in the DC house is somewhat different than that of a car it is envisioned that modifications may have to be made when transposing car technology to the house.

B. Interacting with the homeowner

The type of control asked from the smart grid controller implied an interaction with the homeowner whenever an intervention is needed. An intervention can be initiated by the homeowner as part of ordinary daily activities associated with living in a smart house, or due to a change in a system activity. There are four basic ways the controller can indicate an interaction has occurred or is needed. The first being to use different colour light indicators, the second is voice, the third is via a computer and the fourth is using a mobile phone. It has been shown by a live study [10] that people preferred to use the mobile phone as an interface to send and receive messages to or from the control system. Therefore the DC house should incorporate all these mechanisms.

VII. CONCLUSION

The proposed integration of intelligent appliances and smart house control technology using a smart grid should deal with the voltage integrity issues and bring the implementation of the DC house one stage closer. The smart grid and the power line communication system technologies and the use of ZigBee chips for intelligent appliances already exist. What is needed is research into optimising all appliances for DC voltage, bench testing intelligent AC and optimised intelligent DC appliances to show what advantages/disadvantages and safety issues DC may have verses AC and to bring together all these technologies in a test house. There exist many wireless communication protocols that could be used as an alternative to PLCN. Fruther work will have to be carried out to test the different communications protocols against each other

VIII. ACKNOWLEDGMENTS

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