FEASIBILITY STUDY ON LOW VOLTAGE DC SYSTEMS USING SMART METER DATA

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ABSTRACT

The introduction of Smart Meter (SM) is a first stage towards Smart Grid to develop future energy system. The main difference of a SM with a traditional meter is that instead of only showing the current usage on the meter itself, it can also communicate the usage details directly to a Distribution System Operator. In order to make overall reduction in energy consumption, increasing awareness about the energy consumption is an important factor. The SM data gives that facility by visualizing the energy consumption in real time. The energy consumption can also be reduced by using low voltage Direct Current (DC) distribution in houses and offices. Several factors have increased the recent interest in DC power system. The number of devices that operate on DC continues to increase in both homes and offices. Most of the devices require Alternating Current (AC) to DC conversion between the AC supply and the DC side of the device. These need of conversion from 230V AC to low voltage DC inside the DC power consuming apparatus results in a low overall efficiency of the AC system. This work focused on feasibility of using 230V AC to 48V DC converter with SM for a house with low voltage DC distribution system.

INTRODUCTION

In the latest years, SMs have been gaining certain popularity [1]. Smart electricity meters have already been introduced in several regions of the world. Europe had an early start in the 2000s. North America and Asia-Pacific are two of the most dynamic market regions of SM today [2]. The European Union has set ambitious energy efficiency targets, which include commonly known "20-20-20"-targets [3], [4]. To achieve the targets, the EU has set directives that have led the member countries of the European Union to set legal framework for the installation of SM. In Europe, Italy and Sweden are the first countries to complete a near full rollout of the SM, while several European countries prepare the take-off [3], [4]. 'Göteborg Energi (GEAB)', the leading Distribution System Operator (DSO) in Western Sweden has installed 263,000 SMs in Gothenburg city and the meters are already in operation [5].

Over the last few decades the world has moved steadily from an electro mechanical to an electronic world. The more electronic appliances are coming day by day, the more it is attracting the people towards DC. According to [8], one of the reasons for growing interest on DC is the increasing number of microprocessor based electronic devices which use DC power internally. Moreover, Most of the recently available devices require AC to DC conversion inside the device. Examples of these devices are PCs, radios, televisions, telephones and other electronic appliances. Energy storage devices such as batteries, mobile phones, and cordless tools, also require AC as an energy source. They are equipped with adapters which convert 230V AC into low voltage DC [8].

Another factor is the increasing number of distributed resources such as solar cells and fuel cells which produce DC power and batteries or other technologies store it in DC form. Batteries of plug-in hybrid vehicles (PHEV) store DC power, which is coming more in near future. Energy is required to convert the source's DC into AC in order to connect to the existing 230V AC distribution system.

This work focused on AC to DC converter and investigated the feasibility of using 230V AC to 48V DC converter with SM. This work is presenting a further developments from the Master thesis [6] performed at 'Chalmers Industrial Technology (CIT)' and it was about feasibility study of using a low DC voltage for the distribution system in houses [7]. In that work, it was assumed that the input voltage to the house is 48 V DC. This DC voltage can come from different sources such as a large central rectifier that converts 230VAC to 48V DC or/and renewable energy sources such as solar cells and batteries. In this work, the input voltage to the house is considered to be 230V AC as it is the present situation. The use of AC to DC converter with the Smart Meter is theoretically analyzed by considering the losses, energy consumption and investment cost for both systems. SM data can help to know real time power consumption of different appliances which can be used to do housekeeping for efficient energy use. In this work, 48V DC is considered due to the fact that the user can handle this voltage level without any serious risk.

LOW DC VOLTAGE AS A SOLUTION

By using a low voltage DC distribution system in the residence, AC to DC conversions losses can be omitted and the use of comparatively less efficient adapters can be discarded and also there will be no power factor issues [9]. Only highly efficient DC to DC converter will be needed to run some of the DC appliances. A DC distribution system in the residence will facilitate to reduce the electro-magnetic interference and also the line losses due to the absence of reactive power [10], less current will be needed to transfer the same amount of power. Losses for distribution of electricity are mainly dependent on the current magnitude and the cable length. Application of DC can therefore be more advantageous.

The majority of the devices used in households or offices only require low power that are possible to be connected directly to the low voltage DC distribution system after removing the AC to DC conversion stage. Most of the commercially available appliances are designed with an input voltage of 12V and 24V and some of the appliances are available at input voltages of 48V [9]. As the low voltage DC appliances have demand of higher currents, it makes feeder losses considerable. As a result the overall efficiency of the appliance becomes low. Feeder losses can be decreased by using higher DC voltages and the chosen appliance voltage for a DC residence is 48V [9]. A main goal of this work is to propose solutions an energy efficient low voltage DC distribution system for houses or offices by using AC to DC converter inside the SM. This distribution system should be able to cope with traditional and local electricity generation and storage systems at the end-user level, from DC sources.

A low DC voltage wiring system of a house is investigated and compared with the wiring of the traditional 230V AC system to observe the economic impact in terms of losses in the wire and converter, internal loss of the device itself, investment cost for new wiring and converter on SM.

Investigation on AC to DC in House

A typical house with some general household appliances is considered for the analysis. Light bulbs and LED lights are considered for AC and DC systems respectively. The power ratings of the investigated loads are in the range of 3 W to 2000 W [11-15]. The on-duration of household appliances is obtained from a survey at houses located in Bangladesh and Sweden. The standby losses of the appliances vary for different appliances from different producer [16][17]. For the calculation of stand by losses, the data of standby power is taken from [18]-[23]. Table 1 shows the power rating, standby power consumption, average ON time and standby time of the appliances.

Table 1 Household appliance with power rating and time of use.

Household Appliances	Power Rating, [W]		Standby Power, [W]	Average ON time in a day, [hr]	Standby Time in a day, [hr]
	230V AC	48V DC			
Light	60	7	0	10	0
32 " LCD Television	156	156	4.5	5	19
Laptop	50	50	4.5	7	5
CPU & LCD Monitor	270	270	3.5	5	19
External Modem	7.2	7.2	1	5	19
Microwave Oven	800	800	2.8	1	23
Refrigerator	125	125	10	12	12
Induction Stove	2000	2000	0	1.5	0
Rice Cooker	500	500	0	0.75	0
Coffee Maker	990	990	0	0.5	0
Dish Washer	1500	1500	1.2	0.55	23.45
Washing Machine	500	500	2	0.63	23.37
Vacuum Cleaner	300	300	0	0.29	0
Iron	1000	1000	0	0.43	0
Mobile Phone Charger	4	4	0.5	5	19
Cordless Phone with answering machine	8	8	3	2	22
Audio Mini System	20	20	8	4	20
Security System	3	3	0	24	0

The length of wires in a house depends on the size of the rooms and power rating of the appliances. The feeder length for the different loads typically varies between 12 m and 80 m [20]. An average value is selected for the investigation. Feeder lengths is considered to be 50 m (phase and neutral) for the appliances of below 200 W power rating and 20 m feeder length is considered for the appliances with power rating greater than 200 W. The required area of the feeder line for each appliance is selected based on the value of current taken by each appliance in both 230V AC and 48 V DC systems [19]. Table 2 shows for each appliance, the value of current taken by, feeder length, size of wire and the resistance of wire.

Table 2 length, size and resistance of wire and current taken by appliance for both AC and DC systems.

Household Appliances	Current, [A]		Wire Length, [m]		Size of Wire, [m2]		Resistance of Wire, [Ω]	
	230V AC	48V DC	230V AC	48V DC	230V AC	48V DC	230V AC	48V DC
Light	0.26	0.15	50	50	1.5	1.5	0.57	0.57
32 " LCD Television	0.68	3.25	50	50	1.5	1.5	0.57	0.57
Laptop	0.22	1.04	50	50	1.5	1.5	0.57	0.57
CPU & LCD Monitor	1.17	5.63	20	20	1.5	1.5	0.23	0.23
External Modem	0.03	0.15	20	20	1.5	1.5	0.23	0.23
Microwave Oven	3.48	16.67	20	20	1.5	4	0.23	0.09
Refrigerator	0.54	2.60	20	20	1.5	1.5	0.23	0.23
Induction Stove	8.70	41.67	20	20	2.5	10	0.14	0.03
Rice Cooker	2.17	10.42	20	20	1.5	2.5	0.23	0.14
Coffee Maker	4.30	20.63	20	20	1.5	4	0.23	0.09
Dish Washer	6.52	31.25	20	20	1.5	2.5	0.23	0.14
Washing Machine	2.17	10.42	20	20	1.5	2.5	0.23	0.14
Vacuum Cleaner	1.30	6.25	20	20	1.5	1.5	0.23	0.23
Iron	4.35	20.83	20	20	1.5	6	0.23	0.06
Mobile Phone Charger	0.02	0.08	20	20	1.5	1.5	0.23	0.23
Cordless Phone with answering machine	0.03	0.17	50	50	1.5	1.5	0.57	0.57
Audio Mini System	0.09	0.42	50	50	1.5	1.5	0.57	0.57
Security System	0.01	0.06	50	50	1.5	1.5	0.57	0.57

230V AC to 48V DC Converter

The converter that is considered for this investigation has a current rating of 20A and the rated power is 960 W. This work proposed to use two converters of same rating for the considered appliances. Kitchen appliances will be connected to one converter and the rest of the appliances will be connected to other converter. High power consuming AC device which still runs on AC such as stove can have the option to run on AC supply by switching the power supply from the converter to the stove when it is need as shown in figure 1. Housekeeping system is required to run the appliances in a way so that the loads do not cross the maximum rating of the converter. For example, Microwave Oven cannot be turned ON when Coffee Maker is preparing the coffee. By using housekeeping system, it might be possible to run all the appliances with these two converters. It may also help to reduce the peak power consumption of the customer and leads to a saving on peak power consumption tariff.

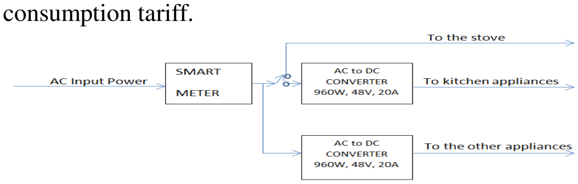

Figure 1 AC to DC converter with the Smart Meter.

Calculations

The following formulas are used to calculate the energy consumption and losses.
The losses in the wire is calculated as

$$P = I^2 x R \quad (1)$$

Where, R is the resistance of wire and I is the current through the wire.
The resistance of the wire is calculated as

$$R = \rho \frac{l}{A} \quad (2)$$

Where ρ is the resistivity and for copper ρ is = $1.7 x 10^{-8}$ Ω m, l is length of the wire and A is the area of the wire.
The total energy loss for an appliance is calculated as

$$\text{Energy loss} = \frac{(\text{Losses in wire} + \text{Rectifier losses}) \, x \, \text{ontimex } 365}{1000} \quad (3)$$

Where rectifier loss is calculated as

$$P_{\text{Rectifier loss}} = 2 \, V_F \, I_{rms} \quad (4)$$

The total energy consumption by an appliance is calculated

$$\text{Energy consumption} = \text{ON Energy} + \text{Standby energy} \quad (5)$$

$$\text{ON Energy consumption} = \frac{\text{ON power } x \text{ ON time per day } x \, 365 \text{ day}}{1000} \quad (6)$$

$$\text{Standby Energy} = \frac{\text{Standby power } x \text{ Standby time per day } x \, 365 \text{ day}}{1000} \quad (7)$$

Table 3 shows the energy loss across the wire, rectifier loss in the appliances, energy loss in the AC to DC Converter, total power consumption in both running mode and standby mode are calculated for both 230V AC and 48V DC system. The standby losses in the appliances are assumed to be negligible for 48V DC system as the transformer and rectifier circuit can be eliminated from the appliances when it runs from 48V DC. The converter that is considered for this investigation has almost 94% efficiency and the losses in this converter is calculated according the efficiency of the converter.

Table 3 Energy loss and energy consumption for both systems.

Household Appliances	Power Loss across Wire, [W]		Rectifier loss in the Appliance, [W]		Energy loss in wire, [kWh/yr]		Energy loss in Rectifier, [kWh/yr]	Energy loss in Converter [kWh/yr]	ON energy consumption, [kWh/yr]		Standby Energy consumption, [kWh/yr]
	230V AC	48V DC	230V AC	48V DC	230V AC	48V DC	230V AC	48V DC	230V AC	48V DC	230V AC
Light	0.04	0.01	0.00	0.0	0.15	0.04	0.00	1.53	219	25.55	0.00
32 " LCD Television	0.26	5.99	1.22	0.0	0.48	10.92	2.23	17.08	284.70	284.70	31.21
Laptop	0.03	0.61	0.39	0.0	0.07	1.57	1.00	7.67	127.75	127.75	8.21
CPU & LCD Monitor	0.31	7.17	2.11	0.0	0.57	13.09	3.86	29.57	492.75	492.75	24.27
External Modem	0.00	0.00	0.05	0.0	0.00	0.01	0.10	0.77	12.78	12.78	6.94
Microwave Oven	2.74	23.61	6.26	0.0	1.00	8.62	2.29	17.52	292.00	292.00	23.51
Refrigerator	0.07	1.54	0.98	0.0	0.29	6.73	4.28	32.85	547.50	547.50	43.80
Induction Stove	10.28	59.03	15.65	0.0	5.63	32.32	8.57	65.70	1095.00	1095.00	0.00
Rice Cooker	1.07	14.76	0.00	0.0	0.29	4.04	0.00	8.21	136.88	136.88	0.00
Coffee Maker	4.20	36.16	0.00	0.0	0.77	6.60	0.00	10.84	180.68	180.68	0.00
Dish Washer	9.64	132.81	11.74	0.0	1.94	26.66	2.36	18.07	301.13	301.13	10.27
Washing Machine	1.07	14.76	3.91	0.0	0.25	3.39	0.90	6.90	114.98	114.98	17.06
Vacuum Cleaner	0.39	8.85	0.00	0.0	0.04	0.94	0.00	1.91	31.76	31.76	0.00
Iron	4.28	24.59	0.00	0.0	0.67	3.86	0.00	9.42	156.95	156.95	0.00
Mobile Phone Charger	0.00	0.00	0.03	0.0	0.00	0.00	0.06	0.44	7.30	7.30	3.47
Cordless Phone	0.00	0.02	0.06	0.0	0.00	0.01	0.05	0.35	5.84	5.84	24.09
Audio Mini System	0.00	0.10	0.16	0.0	0.01	0.14	0.23	1.75	29.20	29.20	58.40
Security System	0.00	0.00	0.02	0.0	0.00	0.02	0.21	1.58	26.28	26.28	0.00

From the above calculation it is seen that the converter has higher loss for induction stove as it draws high current. For this case wire needs to have large diameter to carry this high current and it will also increase the cable price. Table 4 shows total energy consumption and total loss for both systems where stove is supplied from AC. Low voltage DC to DC converter might be needed for some appliances but DC to DC converters usually have very high efficiency. The losses of these converters are neglected in this calculation.

Table 4 Total energy consumption and total loss for both systems.

Household Appliances	Total Energy consumption, [kWh/yr]		Total Energy loss, [kWh/yr]	
	230V AC	48V DC	230V AC	48V DC
5 Lights	219 * 5	25.55 * 5	0.15 * 5	1.57 * 5
32 " LCD Television	315.91	284.70	2.70	28.01
Laptop	135.96	127.75	1.07	9.24
CPU & LCD Monitor	517.02	492.75	4.43	42.65
External Modem	19.71	12.78	0.10	0.78
Microwave Oven	315.51	292.00	3.29	26.14
Refrigerator	591.30	547.50	4.58	39.58
Induction Stove	1095.00	-	14.20	-
Rice Cooker	136.88	136.88	0.29	12.25
Coffee Maker	180.68	180.68	0.77	17.44
Dish Washer	311.40	301.13	4.29	44.73
Washing Machine	132.04	114.98	1.15	10.29
Vacuum Cleaner	31.76	31.76	0.04	2.84
Iron	156.95	156.95	0.67	13.28
Mobile Phone Charger	10.77	7.30	0.06	0.44
Cordless Phone	29.93	5.84	0.05	0.36
Audio Mini System	87.60	29.20	0.23	1.90
Security System	26.28	26.28	0.21	1.60

Comparison Between AC and DC Systems

Table 5 shows the sum of total energy consumption and total loss for 230V AC system and also for 48 V DC systems when only the stove is supplied by AC voltage.

Table 5 Sum of total energy consumption and total loss.

Total Energy Consumption, [kWh/yr]		Total Loss, [kWh/yr]	
For 230V AC	For 48V DC	For 230V AC	For 48V DC
5189.67	3971.20	38.87	273.57

Reduction in energy consumption for low voltage DC system is 1218.47 kWh/yr but the increased energy loss in wire is 234.7 kWh/yr. For the proposed low voltage DC system, the net energy saving per year is 983.77 kWh.

Cost Analysis:

For the cost analysis, new investment cost for low voltage DC wiring is calculated and compared with the wiring cost for 230V AC. The price of the converter is also considered for the investment cost calculation. Total price of energy consumption and the energy loss are calculated for both systems by assuming the price of energy as 1 SEK per kWh. The price unit for the calculation is presented in SEK as the work has been done in Sweden. The total length of wire of this investigation is 740 meter. Average price of wire [21] for different cross sectional area and the length of wire for both systems are shown in Table 6.

Table 6 Prices and lengths of wires.

Area of wire, [mm^2]	Price per 100m, [SEK]	Length used for 230V AC	Length used for 48V DC
1.5	560	720	600
2.5	860	20	80
4	1250	-	40
6	1800	-	20

The total price of wire for the proposed low voltage system is 4908 SEK which is 704 SEK higher than the total price of wire for 230V AC system. The price of the converter that is considered for this investigation is about 2000 SEK.

Total investment cost for each system = wire cost + converter cost (for DC only) + energy loss cost for 20 years. (8)

For 20 years life span of the considered systems, total cost increased for proposed DC system by 9397 SEK. From low voltage DC system net energy saving is 983kWh/yr due to reduced energy consumption. By assuming the price of energy as 1 SEK/ kWh, the net saving from the proposed low voltage DC system per year can be 983 SEK (114EUR). Hence, the payback time of new investment cost will be almost 9.5 years.

CONCLUSIONS:

This work proposed a low voltage DC system with housekeeping for houses where input voltage to the house is AC and all the appliances will run on DC except the stove which runs on AC. The result of this investigation shows that although using a converter for the proposed low voltage system introducing a new loss in the converter and requires investment for new wiring but in total it can save 983 kWh per year for the considered house. By only saving energy, the new investment cost for converter and new wiring can return back after certain period. In addition to this, there can be several other benefits of using low voltage DC house such as the appliances will not require transformer and rectifier anymore. So, the price, weight and size of the appliance will be reduced. This work considered only a house, so in larger perspective it can bring a huge amount of energy saving for the country. As DC is getting more common due to recent development in Smart home appliances which run on DC, using AC to DC converter with the SM for low voltage DC house might be a solution for future. SM can play an important rule for housekeeping with Smart appliances. As a future work for the proposed DC house, the electronic appliances that run on low DC voltage need to redesign by eliminating the transformer and the rectifier of those electronic appliances. The appliances which only run on AC, i.e, stove, dishwasher need a DC solution for future. A new DC solution for these appliances was proposed in [6].

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