Plug-in Hybrid Electric Vehicle Energy System Using Home-To-Vehicle And Vehicle-To-Home: Optimizaton of Power Converter Operation

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***Abstract*—Plug-in Hybrid Electric Vehicles (PHEVs) are seen to be a step forward in vehicle electrification, to replace ICE based conventional vehicles. Using a PHEV implies that part of the vehicle energy comes from the grid or other sources, such as renewable energy, to charge the battery. However, renewable energy sources being intermittent sources, these new needs would only shift the problem by increasing the number of nuclear and coal power plants, and will not permit solving the problem of pollution or fossil fuel depletion. There is a need to optimize the way, in which the available resources are utilized, in order to reduce dependency on nuclear and coal power plants. This will achieve the overall goal of minimizing pollution, reducing the depletion rate of fossil fuels, as well as reduce the overall cost.**

This paper proposes a hybrid power system for house energy needs by utilization of renewable energy sources, grid, as well as the PHEV battery source. Emphasis of paper is on optimization of the overall cost of the system, by selecting the most cost effective and feasible option among the available options; namely, renewable energy sources, the grid and the battery of the PHEV. As a prerequisite to the implementation of this scheme, it is desirable to work out an approximate amount of available energy. For this, the efficiencies of the various power converters involved must be determined and taken into account to reduce the energy losses.

***Index Terms*—Control strategy, electric vehicles, power converters, vehicle power systems.**

I. Introduction

The challenge for the next few years is to reduce Green House Gas (GHG) emissions from vehicles for global warming curtailment. GHG emissions are mainly due to Internal Combustion Engines (ICE) used in transportation. To decrease this emission, a viable solution lies in using non-polluting electric vehicles. New transportation penetration has affected energy production in a major way. Energy production is already reaching peaks. At the same time, load demand has drastically increased. Hence, it has become imperative to increase daily energy production. It is well-known that world energy requirement is mainly catered by nuclear and thermal power plants which are not environment friendly. There is a need to go for renewable energy sources which are both environment friendly and cheap at the same time.

This paper considers a control strategy including converter efficiencies, which consists of the local network, where the home is connected to renewable sources, in addition to the grid. The PHEV's battery can be connected to home, either to charge the battery, or to transfer its energy to the home (V2H), depending upon its state-of-charge (SoC) and the energy requirements of the home load.

II. Problem formulation

The more recent electricity utility trend is to make use of electric, hybrid electric, and plug-in hybrid electric vehicles (EV, HEV, and PHEV) [1], for storage and/or production of energy (Figure 1 [2]). Power conditioning efficiency values can typically be higher than 90 % [3]. EV/PHEV batteries can supply the electric motor of the vehicle, when it is not connected to the house. When the EV/PHEV is connected to the house, it can assist the supply grid for household loads. This power flow is called vehicle-to-grid, V2G. There are several issues to be addressed in V2G [4]. In this paper, the V2G power flow is more specifically called vehicle-to-home, V2H. When the home is supplied using an EV battery pack, household peak consumption can be reduced. Moreover, the EV battery can be charged during the night, when energy consumption is low.

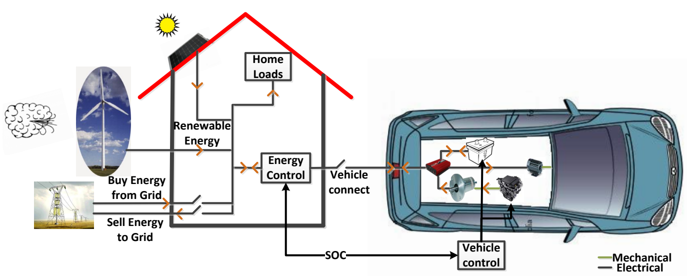


Figure 1. Global diagram

The aim of the home control (HC) Energy Control (EC) Figure 1 strategy is to process, which energy fits best for electrical consumption. There exists a choice between the renewable energy source, the grid, or the PHEV's battery. The choice depends on availability of renewable energy, the battery SoC of the battery, and grid cost operation. The first choice is, obviously, the renewable energy source, since its cost is zero. In case the available power from renewable energy sources falls short of the requirement, the controller has to select between the battery and the grid, based on the battery SoC as well as grid cost operation.

An optimization algorithm has been developed in the past by the authors [2], using the dynamic programming technique developed by Sundstrom and Guzzella [5], to identify the most appropriate energy source from the available options. However, the system has two major concerns: the converter losses which include losses at every step of conversion and hence reduce the overall efficiency of the system, and the battery life cycle. In section III, the losses in each component of the converter is discussed and calculated. The battery life cycle is not discussed in this paper, it will be discussed in detail in a future paper.

To make a more accurate choice, the controller must have knowledge of the exact amount of energy it can obtain from each of these sources. To determine the accurate amount of available power, the efficiencies of the power electronic converters have to be considered. Figure 2 shows the the system configuration under study, along with the converters, which are essentially sources of losses.

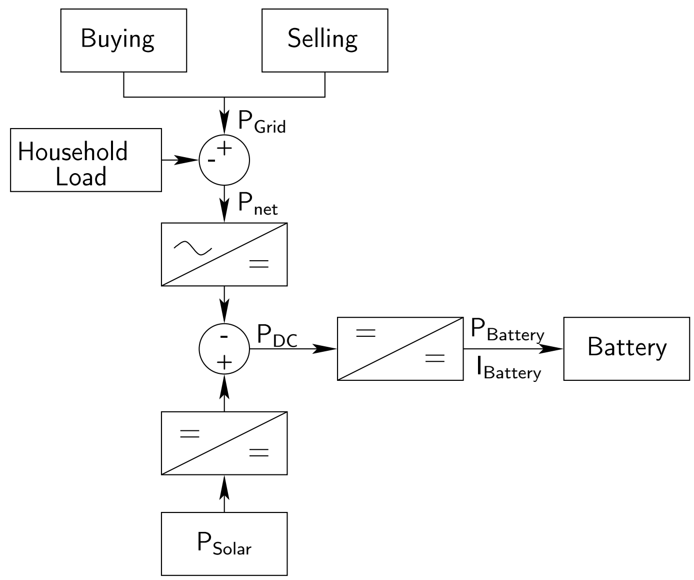


Figure 2. System diagram

III. Converter losses calculation

The converter efficiency depends upon several factors including the components used and switching frequency. Converter losses include conduction, blocking, and switching losses [4], [6], [7], [8]. The converters in the case are a bidirectional DC/DC converter, a unidirectional DC/DC converter and an inverter. The conduction and switching losses in all the components are calculated separately and summed up to obtain the total losses. The efficiency is then calculated in (1)

$$\eta = \frac{Input\_Power - \sum(losses)}{Input\_Power} \tag{1}$$

A. IGBT losses

IGBT losses is divided in two categories, one is conduction losses and the second is switching losses.

1) Conduction losses: The conduction losses is determined by the equivalent IGBT diagram: voltage source in series with a resistance. The equation to calculate the conduction losses $P_{\text{conduction}}$ is given in (2) [4], [9]

$$P_{\text{conduction}} = F_{\text{sw}} \cdot \int_0^{\frac{1}{F_{\text{sw}}}} (V_{\text{s}} + R_{\text{on}} \cdot I_{\text{c}}) \cdot I_{\text{c}} \cdot dt \qquad (2)$$

where :

V_s	:	Forward voltage drop (V)
R_{on}	:	On state resistance (Ω)
I_c	:	Collector current (A)
F_{sw}	:	Switching frequency (Hz)

2) Switching losses: The switching losses can be calculated from the datasheet details as explained in [9]. First and foremost appropriate polynomial equation in Ic, for E_{on}, E_{off} and E_{rr} are obtained from the graphs provided in the datasheets (Figure 3).

This procedure includes noting down the values from the curves and then fitting a second order polynomial approximate equation by using a math tool, such as the Trendline tool in Microsoft Excel®. Figure 3 shows the IGBT switching approximation giving the turn-on (E_{on}) and turn-off (E_{off}) IGBT energy and the diode reverse recovery energy E_{rr} plots. By using the Trendline tool, quadratuc equations approximating the loss curves E_{on}, E_{off} and E_{rr} are obtained. For the IGBT [10] these equations are obtained as given below (3)

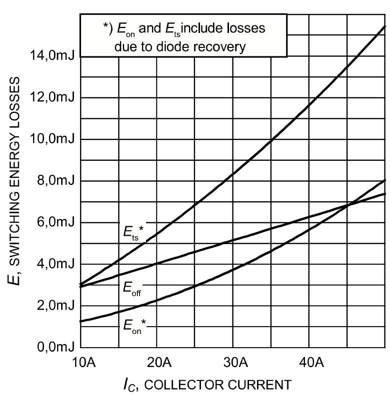


Figure 3. IGBT datasheet

$$E_{\text{on}} = 0.00218 \cdot I_{\text{c}}^2 + 0.041 \cdot I_{\text{c}} + 0.6105 \qquad (3a)$$

$$E_{\text{off}} = -8 \cdot 10^{-5} \cdot I_{\text{c}}^2 + 0.118 \cdot I_{\text{c}} + 1.7095 \qquad (3b)$$

$$E_{\text{rr}} = 0.0021 \cdot I_{\text{c}}^2 + 0.1659 \cdot I_{\text{c}} + 0.9329 \qquad (3c)$$

The switching losses fitted curves should be checked with the original curves to ensure they are close approximations. This checking is performed by placing the approximated curves obtained by mathematical tool on the same graph of the manufacturer datasheet.

B. Inductor losses

This study includes the copper losses in the inductor [6] P_{induc} which is calculated as in (4).

$$P_{\text{induc}} = R_{\text{L}}(I^2 + \frac{\Delta I^2}{12}) \qquad (4)$$

where :

R_L	:	Equivalent series inductor resistance (Ω)
I	:	Current through the inductor (A)
ΔI	:	Ripple current

C. Diode losses

The diode conduction losses are calculated as in (5)

$$P_{\text{D}} = R_{\text{D}} \cdot I_{\text{on}}^2 + V_{\text{D}} \cdot I_{\text{on}} \qquad (5)$$

where :

P_D	:	Diode conduction losses (W)
I_{on}	:	ON state diode current (A)
R_D	:	On state diode resistance (Ω)
V_D	:	Diode voltage (V)

IV. CONVERTER TOPOLOGY

In this study the converters are an unidirectional DC/DC converter, a bidirectional DC/DC converter (to provide for the charging and discharging modes of the battery) and an inverter were simulated and the efficiency curves were plotted with respect to frequency and input power. The bidirectional converter acts as a buck converter during the battery charging mode and as a boost converter during the battery discharging mode. The plot of efficiency v/s input power and frequency for each of the converters is presented in this section.

A. DC/DC Converters

In this study basic DC/DC converters are used, a bidirectional converter with the topology as shown in Figure 4 and the other a buck converter with the topology as shown in Figure 7

Firstly, the efficiency is relating to the switching frequency. According to the following graph (Figure 6), for both bcuk and boost converters, the maximum efficiency is obtained when the

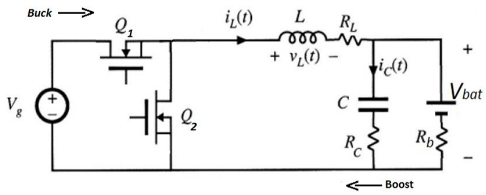


Figure 4. Bidirectional DC/DC Converter

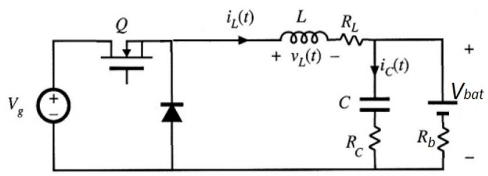
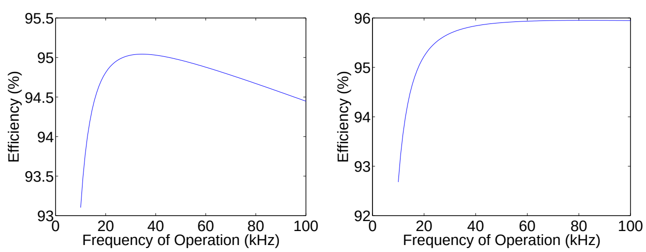


Figure 5. Buck converter

switching frequency is 40 kHz(Figure 7).

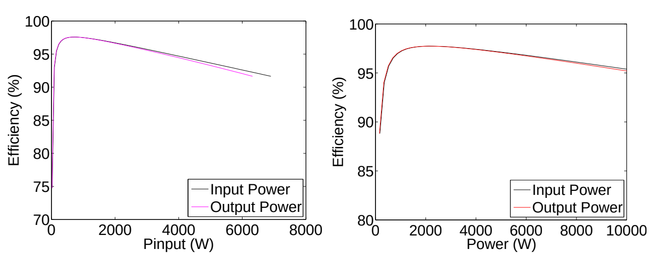
Secondly the boost mode should work between 500 - 1000 W



(a) Boost frequency characteristic (b) Buck frequency characteristic

Figure 6. Buck and Boost frequency characteristic

(Figure 7(b)) whereas the the buck mode between 1000 - 3000 W (Figure 7(a)) to have the best efficiency.



(a) Boost efficiency characteristic (b) Buck efficiency characteristic

Figure 7. Buck-Boost efficiency characteristic

Curve fitting has been done for the efficiency curve for boost operation and the equation for the same is given in (6) and similarly for buck operation the equation is as given in (7).

$$\eta_{\text{boost}} = -0.0006739 \cdot P_{\text{in}} + 97.12 \tag{6}$$

$$\eta_{\text{buck}} = -0.001087 \cdot P_{\text{in}} + 89.83 \tag{7}$$

B. Inverter

The topology which is used is a H bridge inverter. The following plot (Figure 9) shows the optimum switching frequency that the inverter should work. In this case the switching frequency, at which the efficiency is maximum is 20 kHz. To

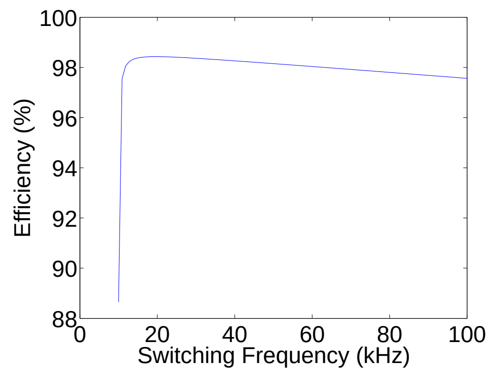


Figure 8. Inverter frequency characteristic

use the best efficiency of this inverter, the input power should work between 250 W and 500 W (Figure 9).

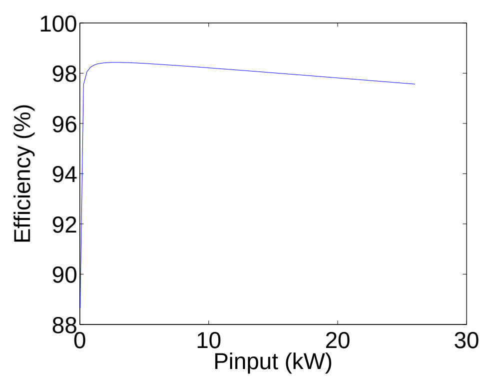


Figure 9. Inverter efficiency characteristic

The curve fitting of the inverter is given in (8)

$$-1.066 \cdot 10^{-05} \cdot P_{\text{in}} + 98.1 \tag{8}$$

V. Study Case

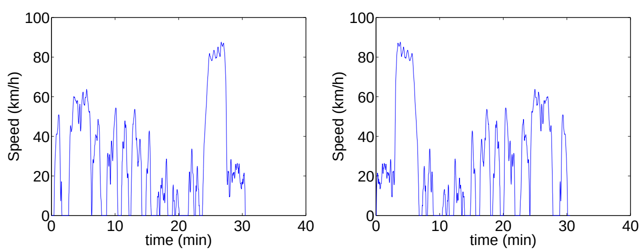
This section describes the scenario which is used for testing the algorithm including the fit equations of converters.

Hour of departure	Drive cycle	Hour of departure	Drive cycle
8	Japan drive cycle 10-15	17	Inverse Japan drive cycle 10-15

Table I
TABLE SCHEDULE EXAMPLE

A. Scenario

The simulation starts at 6 AM in the morning and finishes at 6 AM the next day morning,considering a normal routine day. The schedule is given in Table I. The driver goes for work at 8 AM and comes back home at 5 PM. The travel home to work is simulated by using the Japan 10-15 drive cycle (Figure 10(a)) and the travel work to home is modelled by the reverse Japan 10-15 drive cycle (Figure 10(b)). The vehicle battery size is 25 Ah.



(a) Japan 10-15 drive cycle (Home to Work)
(b) Inverse Japan 10-15 drive cycle (Home to Work)

Figure 10. Drive cycle

In France, the grid on-peak and off-peak hours are defined as in Figure 11; between 10 PM and 6 AM it is the off-peak period and the rest of the day it is on peak period (Figure 11).

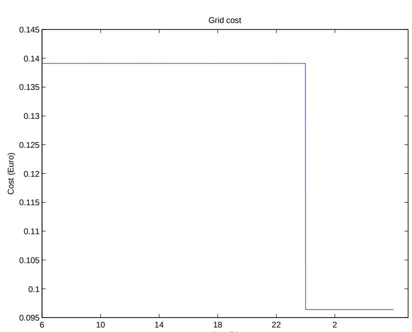
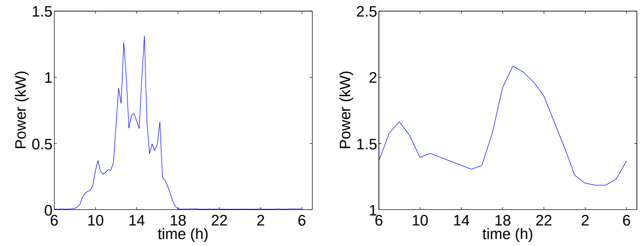


Figure 11. Grid cost

In the figures Figure 12(a) and Figure 12(b), the solar power and the household consumption respectively, which are used in this simulation are shown.



(a) Solar production
(b) Household load production

Figure 12. Household production and consumption

B. Results

The battery behavior shown in Figure 13 describes the best behavior of a battery. Indeed, the battery discharges during the on-peak power, before the driver leaves home. Then, the battery continues to discharge from home to work; the vehicle does not use the ICE. Once the vehicle is parked there is no further changes in the battery state. In this study the battery charging at business place is not considered. At the end of the business day, the driver comes back home and the battery is only used to propel the vehicle to home. Once back at home, the battery helps the grid to supply the household load until the off-peak hours start. During this time the battery is charged to prepare the next day. To prepare the next day, a constraint has been implemented in the optimization algorithm, that is the initial SoC has to be the same as the final SoC. This constraint allows to have a repeatable system.

From 10 PM to 6 AM, the grid energy is greater than the household consumption and the battery will be charged since it is off-peak power.

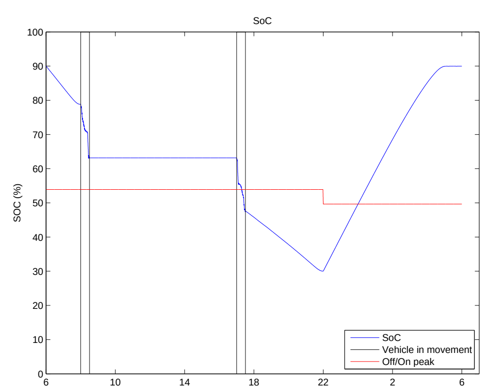


Figure 13. Battery State of Charge

On Figure 15, the buck-boost converter which is implemented between the P_{dc} and the vehicle battery (Figure 2), the

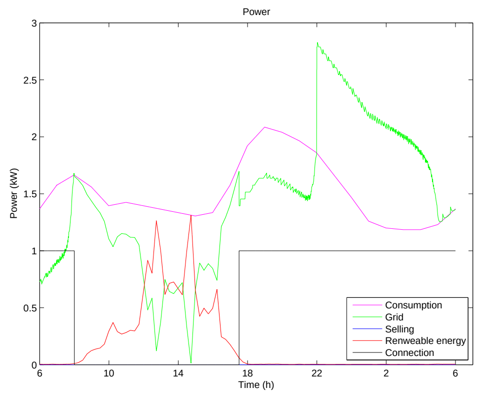


Figure 14. Powers

efficiency varies if the battery is supplying household load or if the battery is charging from the grid. In the boost mode the converter is working always arround its maximum efficiency whereas in the buck mode it is not alsway the case. To work at this efficiency allow to smooth the grid power when the vehicle is charging. If the losses are not taking into account the control strategy can allow the converter to work at low power and that generates energy losses.

The other converter graphs do not play a significantly role in the losses because they work always at the same efficiency.

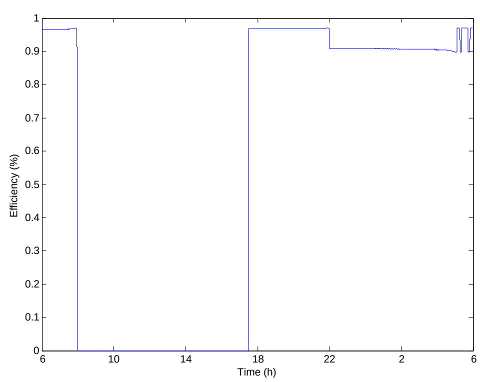


Figure 15. Buck-Boost Operation

VI. Conclusion

The converter efficiency plays an important role in determining the exact amount of power available to the user. The efficiencies of various converters have been estimated by taking into consideration the non idealities of the components of the respective converter.

This graphs and plots presented in this paper corresponds to basic converters. But the procedure can be adapted to any converter once the converter is chosen since the losses calculation procedure or approach for each component of the converter remains the same.

More, to implement converter losses allow the grid power to be smooth and then uses a significant amount of energy from the electric grid.

This system has more losses than the regular system because of the step conversion. However the losses are less compared to the gain of reducing the peak power during the evening, when the vehicle helps the grid to supply household load.

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