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Optimal Energy Allocation and Sizing in EVs for Hybrid Energy Storage System Consisting Battery and Super Capacitor

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Abstract

In the modern era of technology urging of urban traveling is notably increase. One of the best solutions is to fulfill this requirement of urbanized transportation Electric Vehicles that could be the best in all. The key problems associated with the short life span and less cost-effectiveness of batteries lead to the constrain in the expansion and establishment of electric vehicles in the market. Over the years to resolve these preceding problems regarding enhancement of both range and lifespan of battery, hybrid energy storage system (HESS) which using both battery and supercapacitor was propound to achieve maximum efficiency. Hybrid Energy Storage System appears promising due to its potential utilization of each operational benefit of both (battery and supercapacitor). As on the fact, the technology of storage such as the power of continuous supply of energy over a long period by the battery is due to its high density of energy, and peak power with rapid response by supercapacitor is due to its high density of power. For the designing and development of multisource Electric vehicles, Hybrid Energy

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Storage System regulated by a new generation smart energy management strategy plays a vital role. Ruled based filter method and Particle swarm optimization technique are used to raise the sizing of battery and supercapacitor and also to decrease battery power stress with improvement throughout its lifespan.

Keywords: Battery, supercapacitor/ultracapacitor, electric vehicle, hybrid energy storage system.

1 Introduction

In almost all of the applications related to Electric vehicles, the power supplied by the storage energy system generally consists of high energy during steady-state mode and high short power picks while the vehicle is in transient mode during accelerating and braking [1]. But in Electric Vehicle battery is the only energy storage system and thus it cannot supply the required amount of powers and energy at the same time to accomplish exceptional performance of battery size as well as its life cycle and excellent driving range. [2],[3]. Thus, it is very challenging to produce a single battery source-based general purposed Electric vehicle to compete with highly effective internal combustion-based vehicles [4]. Reports say keeping this in mind many kinds of research, development, and initiatives are taken on the concept of a hybrid storage system to optimize the required performance by electric vehicles. Among them, one of the most acknowledged solution is battery and supercapacitor based hybrid energy storage system as battery provide high energy density and supercapacitor provide high power density storage system which gives a design to the system which is light in weight with the longer life cycle of battery and overall high efficiency with good performance of the system,[5-6]. During designing. and development of multiple source electric vehicles for controlling the hybrid energy storage system there is a key role of smart energy management. In a hybrid energy storage system, the basic role of the supercapacitor is to keep battery power as stable as possible by the constant implementation of low to high power during transients to decrease power stress on the battery. Which increases and improve the service of the overall system for the entire lifetime. But the main issue is there’s a difficulty in energy management and sizing of battery and supercapacitor in battery and super capacitor-based hybrid energy storage system [7]. That means to delineate the optimal power flow between the battery and supercapacitor is necessary to decrease battery stress and ultimately lead to an increase not only in lifespan but the efficiency of the overall system. Therefore, the optimization technique for controlling the parameters is used for energy management. For getting a prolonged lifecycle of battery with remarkable improvement in comprehensive efficiency it is highly required to achieve the optimal power distribution between the hybrid energy storage system by significantly design the energy management strategy and system. For this, in recent years many researchers have been inventing energy management strategies. The rule-based approach usually acquired confirming to engineering experience, mathematical models, heuristics, or the intuitions. While optimization-based approach can be further divided as Global optimization and Real-time optimization respectively. The first one i.e. global optimization includes neural networks, convex programming, dynamic programming with many other multi-objective algorithms of optimization. Here rule-based filtering method is proposed for energy allocation cum management and sizing of HESS combining with Particle Swarm Optimization for achieving optimal count of battery and supercapacitor. Here particularly urbanized transportation is under consideration so a small car is considered. Sizing problem is developed for the Indian driving cycle which was extracted from ADVISOR. Here rule-based filtering method is proposed for energy allocation cum management and sizing of HESS combining with Particle Swarm Optimization for achieving optimal count of battery and supercapacitor. In this paper optimization of cost and loss of battery and supercapacitors combination wiz, HESS is achieved while other components of EV represented by constant efficiency [8-9] with reasonable approximation.

2 Hybrid Energy Storage System

Figure 1 which exhibits the general structure of HESS design where DC/DC converter is applied with a control circuit, whose main work is to control battery and supercapacitor simultaneously. However, the DC bus voltage should contain a constant value which is higher than both battery and supercapacitor voltage. Besides, the main question in the Hybrid energy storage system is how to protect as well as control the battery and the supercapacitor. A process to find the answer to this probably plays the key role in motivation to research in the field of HESS in association with hybrid battery and supercapacitor based on the control strategy for the regenerative braking scheme in electrical vehicles. This module contains an

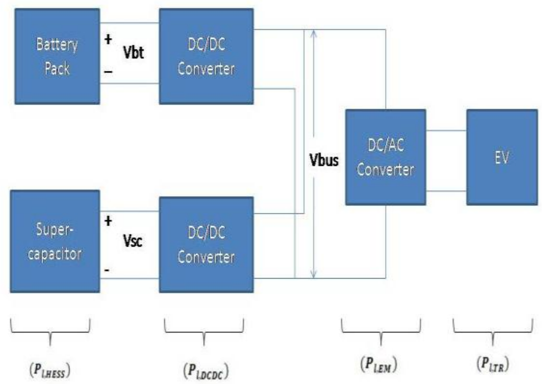

Figure 1 Structure of HESS design

extra control circuit with two DC/DC converters, thus it results in the best control effect. The DC bus voltage is maintained by the DC/DC convertor.

2.1 Model of Battery

We cannot directly measure the charge (q) which is stored in battery with the help of automotive battery systems nonetheless a variation charge of battery can be related to the discharge current by charge balance [10],

$$I_b = \frac{dQ_b}{dt} \quad (1)$$

If we need to evaluate the state of charge (SOC), a significant fact to note in the account is that a fraction of current cannot covert into charge. Because this fraction is due to an inevitable parasitic reaction occurs within the battery. Hence, many times it is considered with the charging or coulombic efficiency

$$\frac{dQ(t)}{dt} = -\eta_c I_b \quad (2)$$

The above two equations are of coulomb counting method which is used to determine the state of charge by measuring terminal current. This method has the advantage of being simple, easy, and reliable until the current measurement is precise. The frequent recalibration points are the core need of this method to recoup the effect ignored by the equations describe above So, from the state of charge(SOC) 's definition, a SOC (q) can be given by

$$S_b = \frac{Q_b}{Q_{bm}} \tag{3}$$

As shown in Fig. 1 a battery with a basic physical model can be derived by taking an equivalent circuit of the system. Here, in this circuit, an ideal open circuit voltage source in series with an internal resistance represented the battery. This equation of equivalent circuit is derived by applying Kirchhoff's voltage law.

$$V_b = V_{ob} - I_b R_b \tag{4}$$

Since the open-circuit voltage represents the equilibrium potential of the battery and it is also a function of the battery charge. It can be represented in terms of interrelationship as,

$$V_{ob} = A + BS_b(t) \tag{5}$$

Here the coefficient A and B are only dependent upon the number of battery cells and construction of battery itself they got no influence by operative variables. Thus, these coefficients are considered as constant with time. The above given mathematical model is considered with a fair approximation of data given in table 1.

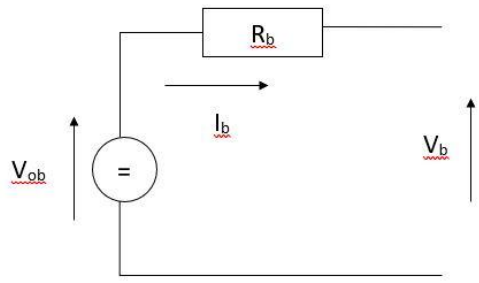

Figure 2 Battery Model

2.2 Model of Supercapacitor

The equivalent circuit is the base for the basic physical model of the supercapacitor. A resistor and capacitor in series made the simple equivalent circuit as shown in fig. 2. The charge's variation can be determined by supercapacitor's terminal current I_{sc} use

$$I_{sc} = \frac{dQ_{sc}}{dt} \tag{6}$$

Likewise, the state of charge (q) and supercapacitor's affine relationship can be explained by the below equation

$$S_{SC} = \frac{Q_{SC}}{Q_{SCm}} \tag{7}$$

$$V_{OSC} = a1 + b1S_{SC}(t) \tag{8}$$

Here, a1 and b1 coefficients have relied upon the number of cells and the physical construction of the supercapacitor. So now, the Kirchhoff's law yields samples of the appropriate

$$V_{SC} = V_{OSC} - I_{SC}R_{SC} \tag{9}$$

This mathematical model is utilizing in optimization problem. Related parameters of this mathematical model listed in table 1.

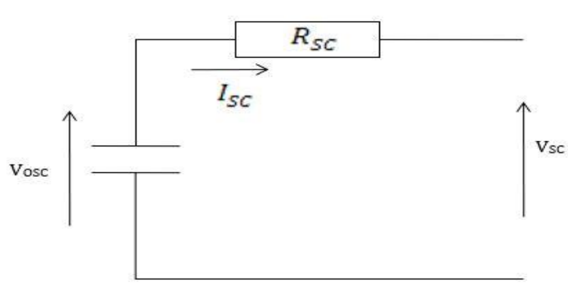

Figure 3 Supercapacitor Model

3 Design and Power Loss of Hess

As HESS delivered the power, it must take into consideration that only power required by the driving cycle but also the losses of power during the powertrain components such as the electric motor, the DC/DC converter, the transmissions, and the HESS.
Hence,

$$P_{in} = P_{out} + P_l = P_{out} + P_l \text{ , if } P_{out \geq} 0 \quad (10)$$

$$P_{in} = P_{out} + P_l = -| P_{out} | + P_{l, ,} \text{ otherwise} \quad (11)$$

$$P_l = P_{lDC/AC} + P_{lDC/DC} + P_{lM} + P_{lTR} + P_{lHESS} \quad (12)$$

It is an assumption that hybrid energy storage system's response can be roughly shown as a voltage – resister model represented in [11] and the energy relaxed within this component are explain by

$$P_{lHESS}= N_b I^2_b Rb + N_{SC} I^2_{SC} R_{SC} \quad (13)$$

So now via two bidirectional boost converter batteries and supercapacitors both are connected to DC bus with identical indistinguishable characteristics. The losses of energy in DC/DC converter are owing to losses conduction in semiconductor, losses in switching, and losses in the passive elements (L and C) as well. All of these three losses can be closely represented by [12].

All parameter was taken into account of real drive. The following equation approximated with a $P_{l\,,DCDC}$
$\eta_{DC/DC}$ is a DC-DC converter efficiency.

$$P_{lDC/DC}= P_{in(DC/DC)}[1- \eta_{DC/DC}] \quad (14)$$

By using the below approximation function, loss for the electric motor in addition to the inverter can be accustomed by [13]. Here η_M is motor efficiency.

$$P_{lM} = P_{in(M)}[1- \eta_M] \quad (15)$$

The transmission forged as a constant efficiency component is known as the vehicle power train [14]

$$P_{lTR} = P_{in(TR)} [1- \eta_{TR}] \quad (16)$$

here η_{TR} is the transmission efficiency.

4 Strategy for the Management of Energy

4.1 Hess Sizing

Hired to breach the power among the sources, the whole process of sizing is lean on to the energy management strategy. There are lots of possibilities for operating this division like machine learning, optimal approaches[15], and simple heuristic like filter based allocation[16]. Where the sizing of a hybrid energy storage system will occur supposing that splitting of power between the sources depends on low and high pass filters. One aspect given by each source will allow us to utilize the filter based allocation strategy. For example, generally, batteries have high energy density with low power density while supercapacitors have high power density with low energy density. Therefore supercapacitor is known as an auxiliary source and gives high power peaks during acceleration and braking which is a high-frequency component of power. During normal running battery provide steady-state power which is the low-frequency power content. It is frequency based along with PSO based power strategy which is an elementary and appealing strategy for the HESS's real-time management. Depend upon this allocation strategy our objective is to find numbers of battery and supercapacitor cells.

4.2 Hess Optimization

Keeping the power required to the HESS in mind we can say it mainly consists of low and high-frequency signals. Therefore,

$$P_{out}(t) = low_t \{ P_{out}(t)\} + High_t \{ P_{out}(t)\} \quad (17)$$

Where low_t and $High_t$ are the first order high frequency and low frequency operator, respectively, with the time ratio γ in seconds, and are defined as,

$$\begin{gathered} low_t \{u(t)\} = \{v(t)|\, \gamma(t) + v(t) = u(t)\}, \\ high_t \{u(t)\} = u(t)\} - low_t \{u(t)\} \end{gathered} \quad (18)$$

extra control circuit with two DC/DC converters, thus it results in the best control effect. The DC bus voltage is maintained by the DC/DC convertor.

In frequency-based allocation, the required number of cells of the battery and supercapacitor is given by the following set these all constraints will also applicable for PSO based optimization for the second stage:

$k_1(X)$ is constraint related to the low power requirement of HESS

$$\geq P_0^{LOW}[x] + \delta_P^{LOW}[x](n_{bt}m_{bt} + n_{sc}m_{sc})P_{sc}n_{sc}\eta_{PT}$$

$k_2(X)$ is constraint related to the high power requirement of HESS

$$\geq P_0^{HIGH}[x] + \delta_P^{HIGH}[x](n_{bt}m_{bt} + n_{sc}m_{sc})e_{bt}n_{bt}\eta_{PT}$$

$k_3(X)$ is constraint related to low energy requirement of HESS

$$\geq E_0^{LOW}[x] + \delta_E^{LOW}[x](n_{bt}m_{bt} + n_{sc}m_{sc})e_{sc}n_{sc}\eta_{PT}$$

$k_4(X)$ is constraint related to the high energy requirement of HESS

$$\geq E_0^{HIGH}[x] + \delta_E^{HIGH}[x](n_{bt}m_{bt} + n_{sc}m_{sc})$$

All Where, [x] = (XT), T is the discrete sampling time, N is different continue points of the taken Indian driving cycle, and n_{mbt}, n_{mSC} is the target min no. of cells.

$$\min_{n_{bt}, n_{SC}, \boldsymbol{\gamma}} c_{bt}n_{bt} + c_{SC}n_{SC} \tag{19}$$

$$s.t. \quad G(\gamma)\begin{pmatrix} n_{bt} \\ n_{SC} \end{pmatrix} \leq H(\gamma), \gamma min \leq \gamma \leq \gamma max \tag{20}$$

However seeing from the practical point of view the set γ prevails with the help of energy and power peaks which is demanded by Electric vehicles. Accordingly for the rapid approximation of γ, it's possible to exchange or replace the above parameters by their upper bounds that allow us to decrease the disparity to four only. By this simplification exhibits errors that can be negligible. Our basic requirement is to get and find several battery and supercapacitor cells based on the above simplification to reduce the cost of the cell at a minimal level.

Where, G and H represent inequalities of the P by matrix notations, which are derived from the above equation. Numerical solver might be faced problems due to γ nonlinearity. To mitigate the problem we solve this nonlinear problem with two practical assumptions, for fixed γ cost function and taken constraints are linear. So the problem can be solved using linear programming to find a nearly accurate solution. We apply PSO with filter-based sizing and energy management as par given flowgraph in figure 4.

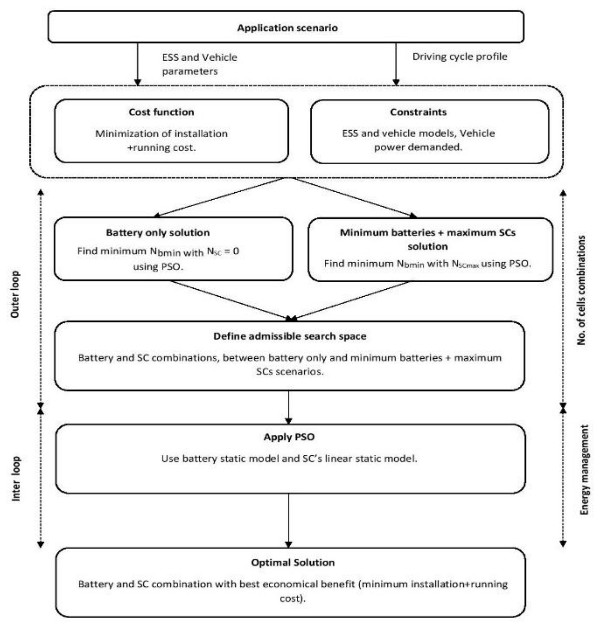

Figure 4 PSO implementation aiding to filter based approach

4.3 Particle Swarm Optimization Design

To resolve whether the calculated values of the variables are proportionate to the constraints we need to implement the PSO algorithm at every time step. Afterward, it needs to be analysed in comparison to the top result of the objective function represented in equation (18) best and among the whole swarm the best is stored as G. Here, inputs to the optimization block are SC model, Battery model, SOC parameters, and electric power demand. All along the time of stimulation the PSO algorithm boot up and go ahead through the system flowchart following each SC's & batteries' optimal number i.e. N_{sc} and N_b, the amount of objective function is calculated. As per the PSO algorithm the answers which are likely will be determined and from the attainable answers the optimal value will be selected.

5 Results and Discussion

Sticking to our prime objective which is the evaluation of the sizing based on filter, this methodology will have to apply to construct battery and supercapacitor based Hybrid energy storage system-HESS competent to provide the need of driving cycle of Indian roads, figure 5 shows the profile of Indian drive cycle. This drive cycle is extracted from ADVISOR. Here, Table 1 describes all the information and details regarding Electric vehicle and energy source parameters. Also we can observe the number of battery and supercapacitor cells and the value of γ which reduces the cost of cells in figure 6. These results also explain that the degree of hybridization of the Hybrid energy storage system (HESS) is controlled by the value of γ. In some cases where $\gamma = 0$, only batteries are employed and thus we get high cost of installation. So remember, increase in the value of γ, decrease the cost, and ultimately reaches to a minimum at $\gamma = 12s$.

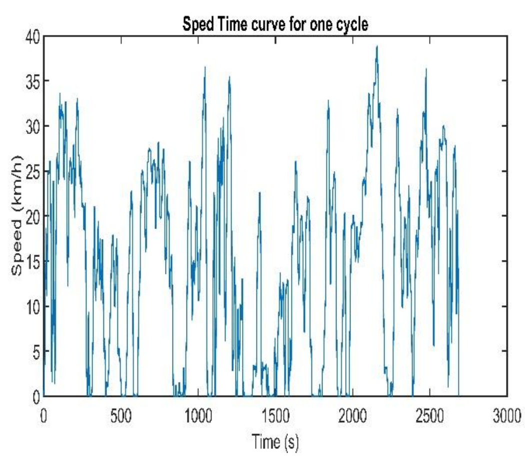

Figure 5 Indian Drive Cycle

But using gamma furthermore means if $\gamma = >12$, it adds to more usage of supercapacitors and thus again increases the cost of HESS. Thence, at gamma

= 12 is the optimal number we get where battery = 69 and supercapacitor cells = 57.

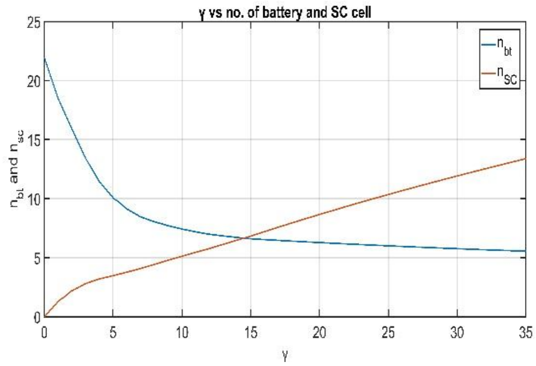

Figure 6 Number of battery and SC cells vs γ

Table 1 Vehicle and Power Train Variables

Parameters	*Value*
Vehicle Mass (m)	750 (kg)
Air density (γ)	1.25 (kg/m^3)
Frontal Area (A)	2.0 (m^2)
Gravitational acceleration constant (g)	9.8 (m/sec^2)
Sampling time (T_s)	1 (sec)
Battery min Voltage ($V_{b, min}$)	2.7 (V)
Battery max Voltage ($V_{b, max}$)	4.0 (V)
Supercapacitor min Voltage ($V_{sc, min}$)	0.0 (V)
Supercapacitor max Voltage ($V_{sc, max}$)	2.7 (V)
Battery resistance (R_b)	2 (mΩ)
Supercapacitor resistance (R_{sc})	2.2 (mΩ)
Battery voltage offset (A)	2.45 (V)
Battery voltage gain (B)	1.25 (V)
Battery max charge ($Q_{b, max}$)	360 (KC)
Battery min SOC ($S_{b, min}$)	0.2
Battery max SOC ($S_{b, max}$)	1
Supercapacitor min SOC ($S_{sc, min}$)	0.05
Supercapacitor max SOC ($S_{sc, max}$)	1
Battery Cell Weight (M_b)	1.1 (kg)
Supercapacitor Weight (M_{sc})	0.6 (kg)
Efficiency of DC-DC Converter	0.98
Efficiency of inverter	0.95
Efficiency of Motor	0.95

Efficiency of transmission system	0.98
Cost of a capacitor cell (C_{cu})	18 ($)
Usable energy of a capacitor cell (E_{cu})	1.4 (Wh)
Maximum power of a capacitor cell ($P_{uc,max}$)	676 (W)
Cost of a battery cell (C_{batt})	100 ($)
Usable energy of a battery cell (E_{bat})	85 (Wh)
Maximum power of a battery cell ($P_{bat,max}$)	300 (W)

Not only the sizing task but the optimal approach also provide the allocation of power between the battery and SC. Power required by vehicle under consideration is plotted in figure 7. power splits among the sources of energy are shown in figure 8 below. And thus its result exhibits that during cruising speed traveling of the electric vehicle the battery should supply the power with the content of low frequency and SC should supply the power with the content of high frequency. Estimation and optimization of running cost is achieved by repeating the simulation for 5 years of life span expectation for an EV in urban utilization. The same is also achieved for only battery which gave higher cost of running in terms of Wh/$. Considering the power components of low and high frequency can be determined by low high pass filter very simply. so this is the best popular method for real-time application is the use of power and energy allocation using filter-based technique. As shown in figure 8 the supercapacitor gives transient peaks to keep stress in limit on the battery during acceleration and braking.

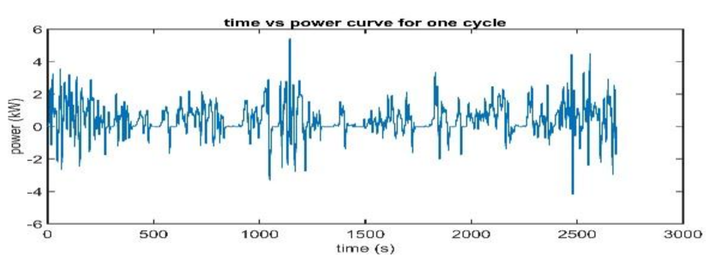

Figure 7 Power Required by EV

Optimized HESS losses are plotted in figure 9 as delta P which gives a clear view of HESS losses for the entire cycle concerning total power delivered to an electric vehicle.

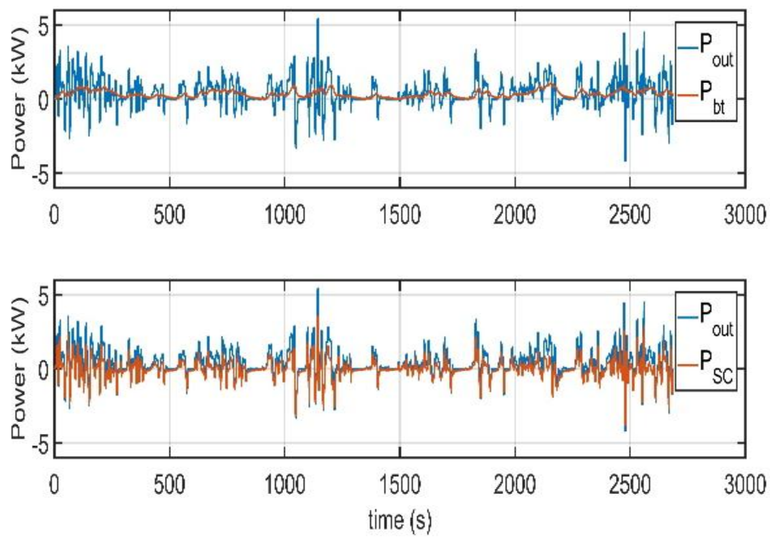

Figure 8 Power allocation between battery and SC

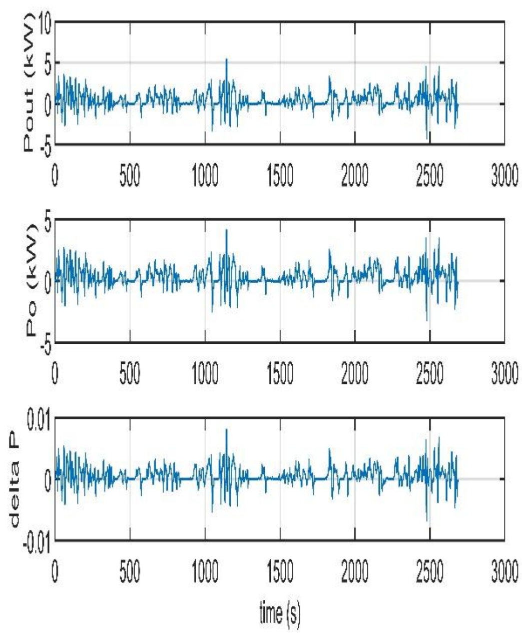

Figure 9 Different Power

6 Conclusions

The basic development of a rule-based filter approach in conjunction with PSO based optimization towards energy management and sizing of the Hybrid Energy Storage System composed of batteries and supercapacitors is established into this paper. To manage the hybrid energy storage system and also to presume that the energy capabilities and peak power of each source are known the filter based with PSO application for sizing applies a frequency power decomposition. This approach defines as a programming problem that is efficient numerically that gives a thorough understanding of the fundamental mechanism associated with the hybridization of battery – supercapacitor. For almost many driving cycles this method provides sizing and energy management. Here the result shows that under the influence of the Indian drive cycle with few assumptions which is practical the aftermath problem of sizing can be taken as a linear programming and can be solved with the help of efficient numerical techniques. HESS is efficiently working compare to battery alone system and extra cost of converter and supercapacitor will be covered as payback in running cost and life expansion of batteries. Among the different combinations of N_b and N_{sc} optimized N_b is 69 and supercapacitor N_{sc} is 57 combination achieves Initial and running cost such that proves that in long run HESS is efficient than battery alone and other combinations.

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