

Review Paper

Low Pass Filter as Energy Management for Hybrid Energy Storage of Electric Vehicle: A Survey

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Abstract

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The transportation sector contributes up to 35% of carbon dioxide pollution. Electric Vehicles (EVs) offer a pollution-free alternative but face a crucial challenge in their battery-based Energy Storage System (ESS). The solution to the battery issues is combining it with other ESS with high power density called a Hybrid Energy Storage System (HESS). Energy Management Strategy (EMS) is used to distribute the power demand in the HESS. Low Pass Filters (LPFs) are one type of EMS that can be used to ensure the smooth flow of power between different energy storage elements. This article focuses on the pivotal role of Low Pass Filters (LPFs) within HESS for EVs, facilitating seamless power flow. The novelty lies in the comprehensive review of LPFs in this context, shedding light on their impact on energy management. Four LPF architecture classes are discussed: fixed cut-off, optimal cut-off, adaptive cut-off, and combination, referencing prior research. Additionally, a critical examination of challenges and limitations is provided, offering insights for researchers and practitioners.

Keywords: Energy management; Electric vehicle; Hybrid sources; Filter

1. Introduction

The transportation sector contributes up to 35% of carbon dioxide pollution [1]. The Electric Vehicle (EV) is one of the solutions to this issue since it is a pollutant-free vehicle [2], [3]. According to Ihsan [4], many countries in the world have promoted the development of the use of EVs to help overcome the problems of the energy crisis and global warming. However, EVs still face some problems compared to conventional vehicles which use an engine [5]–[7]. Batteries are mainly used as energy storage systems (ESS) in EVs [8], [9]. The major problem of the EV is the ESS which is mainly based on the battery. The battery has low power density which makes it cannot give high instantaneous power for acceleration [10], [11]. Moreover, the high current can reduce the lifespan of the battery.

The solution to the battery issues is combining it with other ESS with high power density called a Hybrid Energy Storage System (HESS). HESS can

improve the performance and efficiency of the system [12]. Supercapacitors and flywheels are examples of high-power density ESS. According to Hemmati and Saboori [13], a battery-supercapacitor is the most promising HESS in EV applications.

Energy Management Strategy (EMS) has an important role in the HESS system [14]. It is used to distribute the power demand to some ESS used. Authors in refs. [15], [16] and [17] classify the EMS method into three which are rule-based, optimization-based, and learning-based. The rule-based method is the most robust and has fast computational time; hence, it is implementable [18], [19]. Therefore, in this study, the filtering method which is part of the rule-based EMS being studied.

Low Pass Filters (LPFs) are the filter types that can be used to ensure the smooth flow of power between different energy storage elements. It is one of the most simple EMS methods [2], [20].



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Whereas according to refs. [21]–[23], it is simple with robust performance and gives good dynamics and cycle reduction. The working principle of LPF in EMS is to decouple low-frequency power and send it to the battery whereas the high-frequency signal is assigned to the supercapacitor, as illustrated in Figure 1.

While previous surveys have explored Filter-Based Control (FBS), they primarily discussed its application in general HESS contexts, such as Distributed Generation Systems (DGS) based on Renewable Energy Sources (RES) [24], [25]. In contrast, this article specifically focuses on the role of LPFs in HESS for EV applications and their influence on energy management. This review is grounded in a comprehensive analysis of pertinent literature from the Scopus database. The contributions of this article can be summarized as follows:

- Review the fundamental principles and architecture of LPFs, their different types, and their application in hybrid energy storage systems.
- Discuss the current challenges and limitations associated with the use of LPFs and suggest future research directions for research in this domain.

This review paper is guided by two central research questions: What is the architecture of LPF

as EMS in HESS EVs? And How to select the cut-off frequency of LPF EMS?

This article aims to provide an extensive understanding of LPFs and their role in improving energy management for EVs. Furthermore, it aims to offer valuable insights for advancing research and development in this field. There are four classes of the architecture of the LPF as EMS which will be discussed. Section II explains the material and method used in this review. While the main part of the LPF review is discussed in Section III including the challenges and limitations. Finally, the conclusion will be provided in Section IV.

2. Material and Methods

This study uses qualitative methods through a literature study on the application of low-pass filters (LPF) as EMS in electric vehicles. Figure 2 shows the step by step of the review process. Starting from identification which searching the related references from the Scopus database during the period of 2013-2022. The keywords used are electric vehicle, energy management, and filter. The subjects are selected for engineering, energy, computer science, and mathematics. The document is written in English with the type of article, review, conference paper, and conference review. There are 452 documents that meet the criteria.

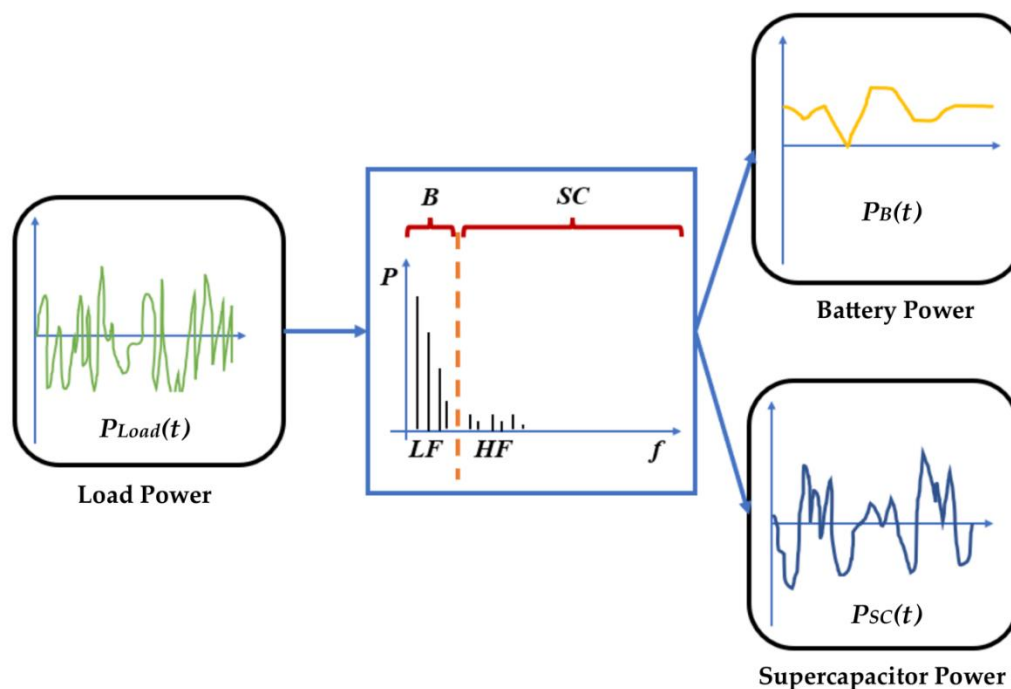


Figure 1. Working principle of LPF as EMS [26]

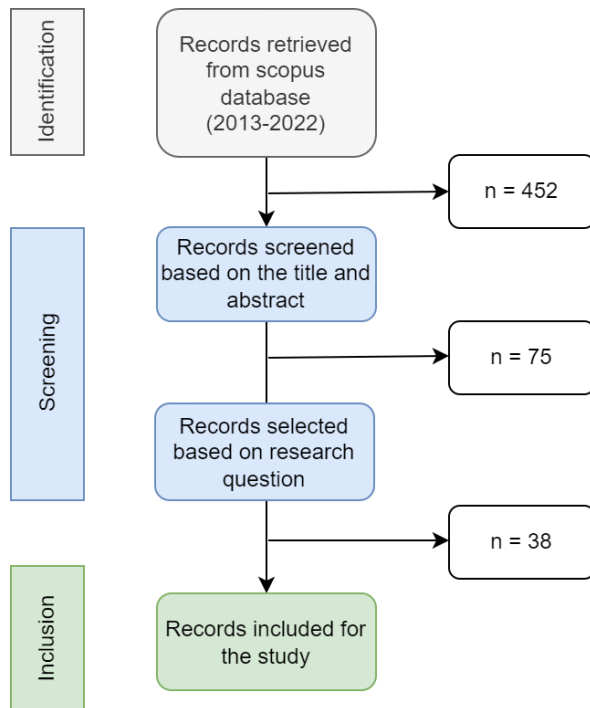


Figure 2. Flow diagram of the review process

The second step is screening. The document is screened based on its title and abstract. Resulting in 75 documents rest. Next, this document is selected based on the research question and 38 documents are relevant to be used. The last step is inclusion, and 38 documents from the previous step are then studied in detail.

3. Results and Discussion

3.1. Fixed Cut-Off Frequency

The fixed cut-off frequency of LPF for EMS can be found by several methods. Some methods that are found in some publications are Ragone plot, Fast Fourier Transform (FFT) analysis, Power Spectral Density (PSD) analysis, numerical calculation, and trial. In this part, this method will be reviewed.

3.1.1. Ragone Plot

The Ragone plot is a plot that shows the relation between power density and energy density of an energy storage system (ESS). The Ragone plot is shown in Figure 3. From this plot, the cut-off frequency is calculated using Eq (1) where f_c , ρ_{power} , and ρ_{energy} is the cut-off frequency, power density, and energy density, respectively [28]–[30]. This method is independent of the drivetrain since

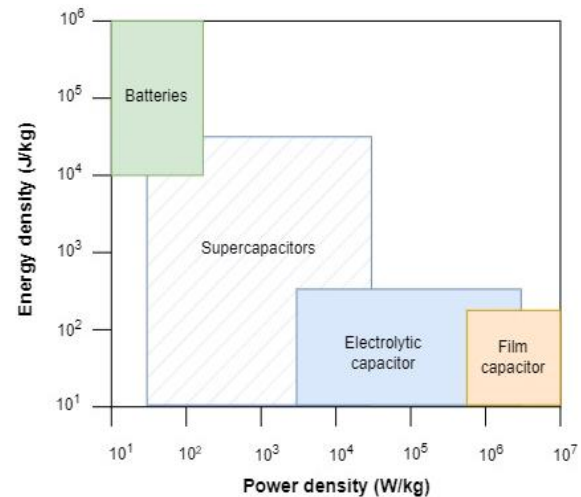


Figure 3. Ragone plot [27]

$$f_c = \frac{\rho_{power} [W/kg]}{\rho_{energy} [J/kg]} \quad (1)$$

only based on the power and energy density of an ESS. This method can give acceptable results even if not as well as another method which accommodates the track information.

The Ragone plot has been proven by some studies such as in [28], [29], and [30]. In [28], they use three power sources which are fuel-cell (FC), battery (B), supercapacitor (SC), and two low pass filters (LPF). The first LPF is used for FC, and the rest power from this LPF is sent to the second LPF the output is for the battery. While the rest from the second LPF is sent to SC. They conclude that this method can utilize the SC's strength in the transient period followed by battery and FC which means could prolong the ESS lifetime.

In [29], they also use the same power sources and a number of filter as in [28]. The system illustration is depicted in Figure 4. They add the analysis further in the sizing of each power source. Whereas [30], also used the same system. However, to improve the performance, they added fuzzy logic as an adaptive algorithm for cut-off frequency for LPF on the battery side.

3.1.2. Spectrum Analysis

Both Fast Fourier Transform (FFT) analysis and Power Spectral Density (PSD) analysis can be grouped into spectrum analysis. The Fourier Transform (FT) is a mathematical method for transforming a signal from the time domain to the

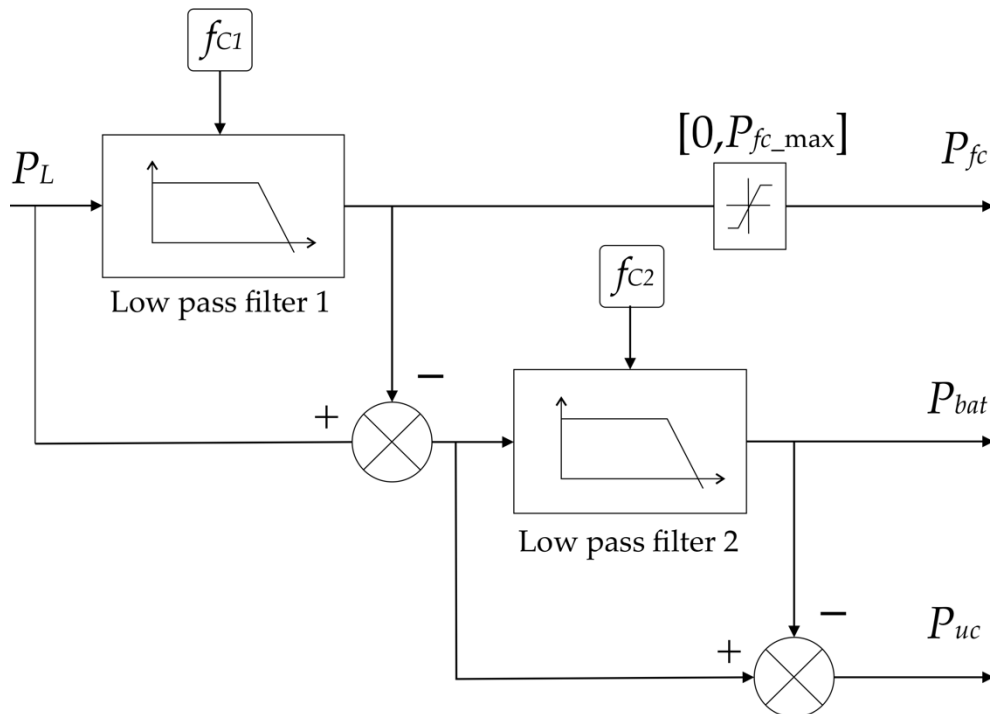


Figure 4. Two LPF for three power sources [29]

frequency domain. Since FT is computationally intensive, the improvement of it which is more efficient in the computational process is Fast Fourier Transform (FFT) [31]. In the case of energy management between more than one ESS, the FFT is used to find the cut-off frequency of the LPF method. The power demand or load current is transformed from the time domain to the frequency domain signal. In the frequency domain, the amplitude of some frequencies can be seen. Hence, the high amplitude, typically found in the low-frequency range, can be allocated to the battery, while the remainder can be designated for the SC. This method is used by [27], [32], and [33].

Hange et al. [32], use FFT to get the cut-off frequency of an LPF which is used as energy management between FC and Lead-acid battery. The process of finding the cut-off frequency is not clearly explained. They validate the performance in both simulation and hardware and conclude that it can maintain the SoC of the Lead-acid battery.

In refs. [27] and [33], they use MATLAB FFT analyzer as shown in Figure 5. The FFT analysis window shows the magnitude of each frequency compared to the fundamental frequency. In ref. [27], the fundamental frequency is derived from cycle drive which is one per period of the cycle in seconds. This method will give a very small fundamental frequency if the drive cycle used has

a long period. They validate the proposed method in Hardware in the Loop (HIL) environment and conclude that this method is simple and effective in real-time control. Whereas in ref. [33], after getting the cut-off frequency for LPF they combine it with a fuzzy logic method. It will be discussed in more detail in the next part.

PSD is a method for analyzing the frequency content of the signal and determining the distribution of power among different frequencies. This method also applies FFT and then calculates the power of each frequency. This method is used to get the cut-off frequency of LPF in EMS [34]. Based on the PSD analysis, they conclude that the cut-off frequency below half of the frequency that has the magnitude of -3dB is sufficient. They compare some digital LPF method which is Butterworth, Chebyshev-1, Chebyshev-2, and Elliptic, and conclude that the Elliptic filter is the most suitable and satisfy the requirement. Simulation shows that a 47% improvement in battery pack SoH (State of Health) can be achieved.

3.1.3. Others

Despite the three methods discussed before, there is also some method used to find the cut-off frequency of LPF in EMS. Ref. [35] uses a numerical calculation based on the rate of change of battery current. Since it is not easy to consider

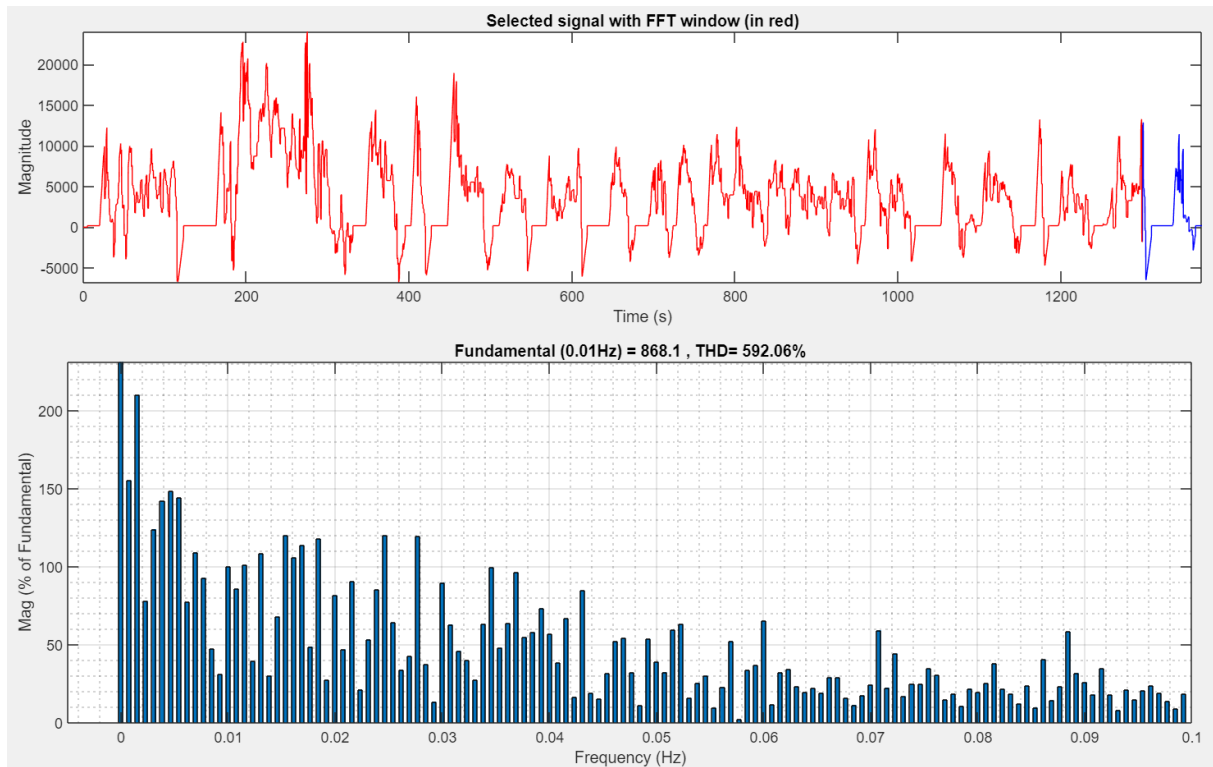


Figure 5. The use of FFT analyzer in MATLAB

$$T = \frac{-t}{\ln\left(1 - \frac{di_{bat}/dt}{\alpha}\right)} \quad (2)$$

all drive cycles, only the acceleration condition is considered. The time constant is derived from Eq (2). Where T , α , and t are time constant, the average rates of change of input current, and minimum acceleration time, respectively. To maintain the SoC of SC they add a rule-based adaptive algorithm.

Another method that can be used to find the cut-off frequency for LPF EMS is by trial and evaluation as studied by Kimura et al. [36]. They set shorter time constant to smooth battery power and not to absorb the regenerative power. Some combinations of battery and SC with a different number were also tested. They evaluate the cut-off frequency using the loss function. In the end, they conclude that the SC can cut the peak power of the battery.

3.2. Optimal Cut-Off Frequency

The optimal cut-off frequency means the cut-off frequency of LPF is searched by the optimization method. Some optimization methods can be used. In ref. [37], they use numerical computation. With the cost function that considers the SoC of SC, they found the

optimal cut-off using iterative. This method is online; therefore, the cut-off frequency changes every time. The software simulation confirms that the proposed EMS can ensure SC's SoC regulation and ensure prominent frequency distribution of power between battery and SC.

Traore et al. [38] propose online optimization of cut-off frequency LPF of battery-SC EV. Since the optimization is done online, the low computational iterative method is used. Simulation testing shows that the proposed method can reduce the electrical losses of the system. However, they do not clearly explain the optimization process but say that it is possible for real-time implementation.

Authors in refs. [39] and [40] use Dynamic Programming(DP) for finding optimal cut-off frequency. In ref. [39] they combine offline and online tuning of the cut-off frequency. The offline is done using DP to find the optimal frequency, while the online method uses a look-up table to make cut-off frequency adaptable based on load current and SC's voltage. In the end, they conclude that the reduction of energy consumption is 23.85% and 7.08% under aggressive acceleration and urban conditions, respectively.

In ref. [40] DP to find the optimal cut-off frequency of a Hybrid Thermal Electric Vehicle (HTEV) which has three energy sources which are thermal engine, battery, and SC. The objective is to minimize the cost of the vehicle mission by an onboard energy mix. After the simulation study, they concluded that the proposed method is effective in handling power sharing between the thermal engine and traction motor, and also between the battery and SC which supply the traction motor.

3.3. Adaptive Cut-Off Frequency

The most used method to improve the performance of LPF as EMS is an adaptive algorithm. Using an adaptive mechanism, the cut-off frequency of the LPF will change based on the determined condition. In this part, some adaptive algorithms proposed by the researcher will be reviewed.

3.3.1. Rule-based

The author in ref. [41] proposed EMS based on a frequency-varying filter to distribute power between the battery and SC in a small-scale EV. The objective of the varying frequency is to maximize the SC utilization. The principle of varying frequency is based on the drive cycle. They accommodate two drive cycles which are urban and highway and determine the different cut-off frequencies for each drive cycle. As shown in Figure 6, a decrease in the cut-off frequency on the highway. On the other side, in urban drive, the

cut-off is increased so that the SC can be charged and discharged less energy every time. Since in urban driving, the frequency of acceleration and deceleration is high. This also can make SC provide long-term energy assistance without charging. However, these sources do not explain how to recognize the drive cycle yet.

After finding the cut-off frequency using numerical calculation, to improve the performance of the LPF EMS, [35] adds the adaptive algorithm. The algorithm is based on rules that consider the SoC of both battery and SC and also the slope of velocity. This algorithm is depicted in Figure 7 where T and a are time constant and gain of the filter, respectively. After testing some conditions in a simulation environment, they conclude that using the proposed method, SC SoC is regulated, and battery loss is decreased compared to conventional filtering EMS.

Authors in ref. [42] propose an adaptive filter based on the rules listed in Table 1. Where T^* , T_{min} , and T_{max} are normal time constant, minimum time constant, and maximum time constant, respectively. However, they do not explain in detail how to get to the upper and lower limits of the time constant. The value of it or the adaptable performance is also not given. After the experimental study, they concluded that the proposed method gives a smart way of using SC power and keeping it in the tolerable operation range.

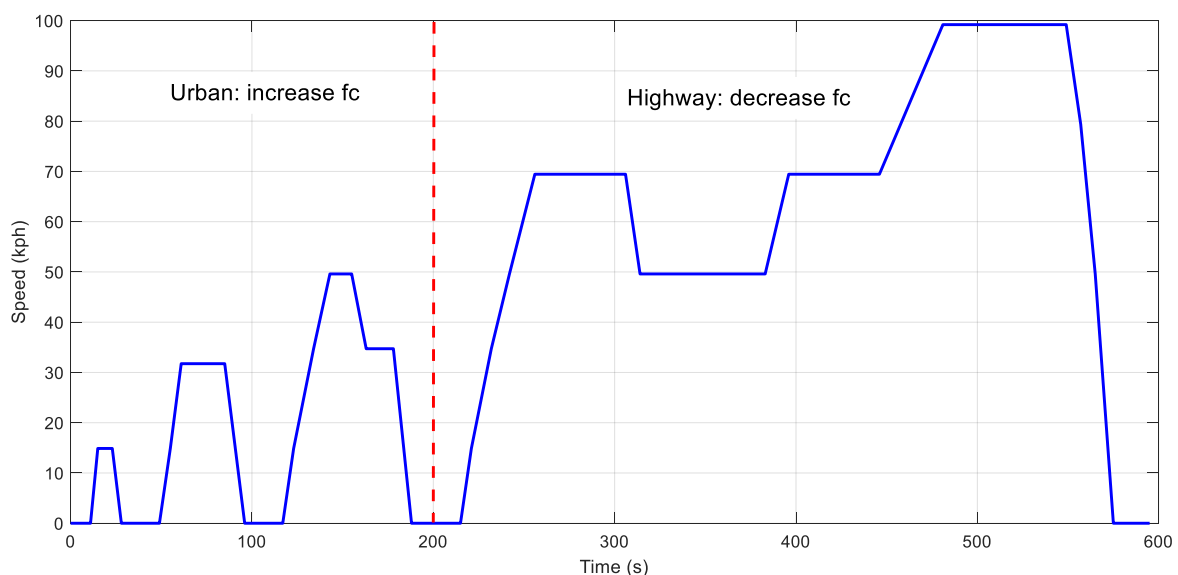


Figure 6. Varying cut-off frequency based on drive cycle [41]

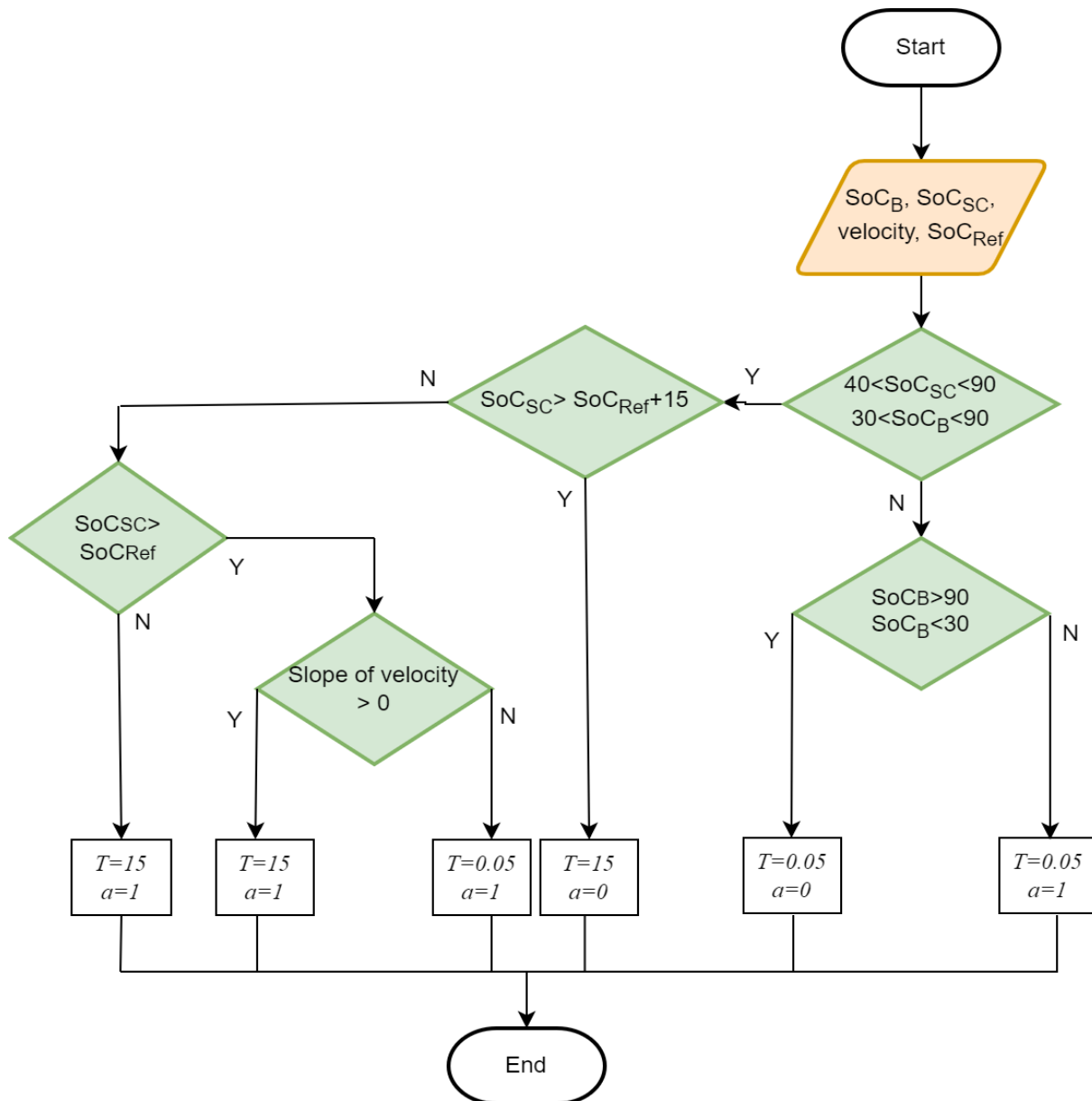


Figure 7. Adaptive cut-off based on rule base [35]

Table 1. Rules of Adaptive LPF used in [42]

Conditions	$V_{sc} < V_{sc-min}$	$V_{sc-min} < V_{sc} < V_{sc-max}$	$V_{sc} > V_{sc-max}$
$I_{Load} > 0$	T_{min}	T^*	T_{max}
$I_{Load} < 0$	T_{max}	T^*	T_{min}

3.3.2. Fuzzy-based

Fuzzy logic is one of artificial intelligence (AI) that uses a rule-based that converts linguistic rules into a decision or control action [43]. It was applied in various areas such as control systems, decision-making, and energy management systems [44]–[46]. In this part, fuzzy logic as an adaptation algorithm for LPF will be discussed.

In ref. [47] they use the information of vehicle speed and power request as the fuzzy input. The fuzzy logic parameters were computed using the

optimization method in MATLAB. After the simulation, they concluded that compared to the fixed cut-off frequency, their proposed method can reduce the losses by up to 62% in the ECE driving cycle (also known as the urban driving cycle (UDC)).

Snoussi et al [29] proposed auto-adaptive filtering-based EMS for EVs with FC, battery, and SC. Since using three ESS, then the LPF used is two as shown in Figure 8. The fuzzy adaptive algorithm is used in LPF for the battery (LPF2).

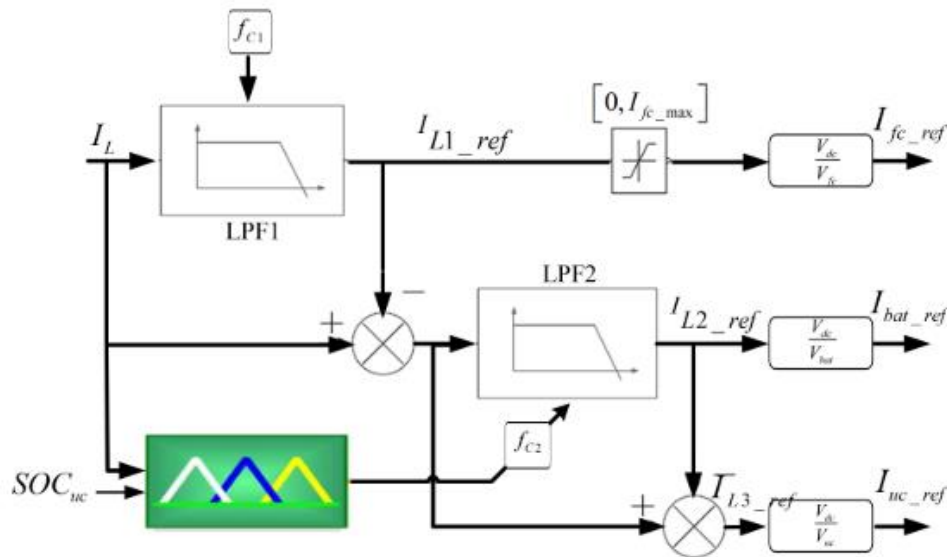


Figure 8. Adaptive cut-off filter of LPF used in [29]

The input of fuzzy is the load current and SoC of SC whereas the output is the cut-off frequency for LPF. The Ragone plot is used to determine the initial cut-off frequency. The cut-off frequency of LPF1 is fixed and derived from the Ragone plot too. The Mamdani type of fuzzy and trapezoidal membership was used in their study. During acceleration, when SC's SoC is high, the maximum energy of SC is extracted; therefore, the f_{c2} is decreased. If SC's SoC decreases, f_{c2} should increase to avoid over-discharge. In braking conditions, the energy should be recovered by SC, hence, f_{c2} also decreases. After SC's SoC increases, the f_{c2} should increase to avoid overcharging. They validate this method using simulation and conclude that durability and autonomy can be improved with minimal cost.

Hussain et al. [48] used a biadaptive controller for EMS of an HEV with battery and SC. The EMS consists of an Adaptive Charge Controller (ACC) which protects SC from over-charging/ over-discharging and Adaptive-LPF(ALPF) which is responsible for power sharing as shown in Figure 9. The ALPF uses fuzzy to adapt the cut-off frequency based on load current and SC's SoC as done by Snoussi et al. [29]. The simulation study shows that the proposed method has less variation in voltage, lower battery loss, and high efficiency.

Zhang et al. [49] also use a fuzzy controller for adaptive filtering-based EMS of battery and SC. They used two loops for controlling the powering and braking as shown in Figure 10. During

powering, the power required (P_{req}) is sent to the LPF where the cut-off is varied by fuzzy. The fuzzy input requires power, battery SoC, and SC's SoC. From the LPF, the power signal is sent to saturation limiting where the limit value is the average of required power. On the other side, in braking conditions, the brake power is directly sent to saturation limiting. The average power value is sent to the battery, while the rest is for SC. After the simulation study, they conclude that the proposed method can perform well which can protect the battery and reduce energy consumption.

3.3.3. Fast Fourier Transform (FFT)-based

Liao et al. [50] proposed adaptive split frequency-based quantitative allocation. It consists of three steps which are power pre-allocation, power spectrum, and power allocation. The first step is to determine the allocation of load power between the battery and SC according to charging and discharging in specific load power conditions. In the second step, FFT is used to determine the cut-off frequency. In the last step, the LPF is used to allocate load power. The output from pre-allocation is the power allocation for the battery and SC. This signal is sent to the power spectrum to determine the cut-off frequency where $K_{bat} = E_L/E_{all}$, Figure 11. Where E_L and E_{all} are the low-frequency range area and all frequency range area, respectively. This mechanism makes FC changes and adapts to the condition. The expe-

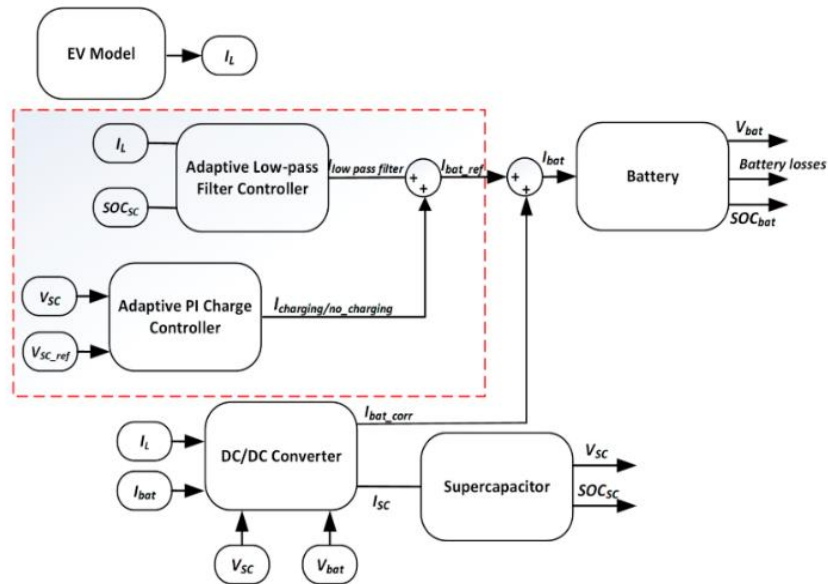


Figure 9. Adaptive LPF with Adaptive charge controller [48]

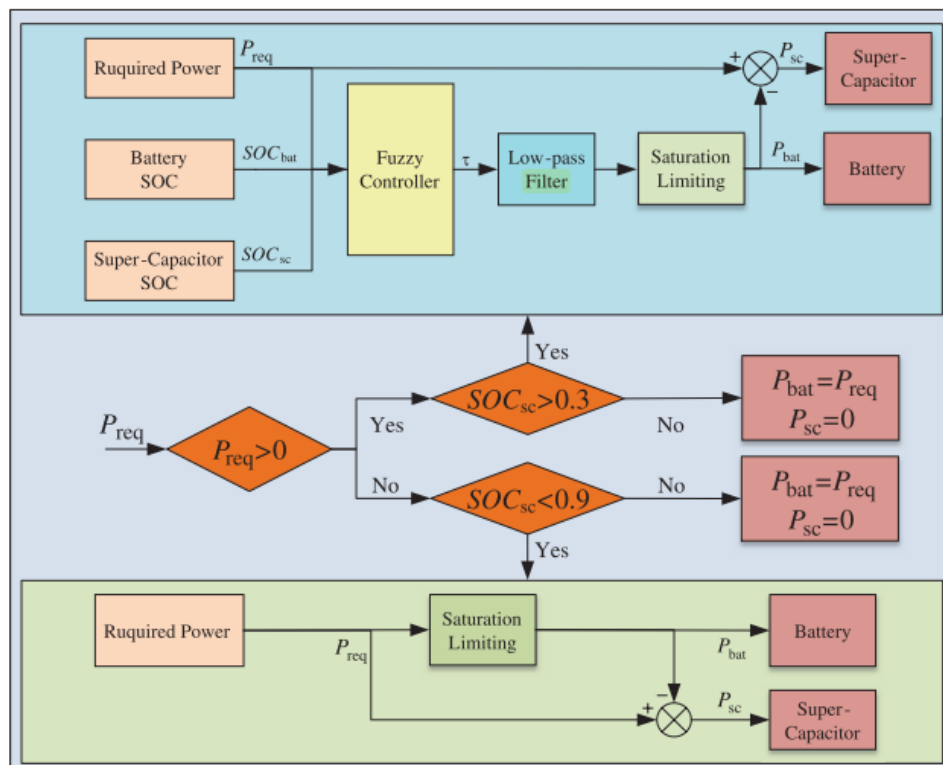


Figure 10. Adaptive Filtering-Based [49]

Experimental results show that the proposed method can improve energy efficiency and protect the batteries.

The author in ref. [51] uses adaptive power allocation to manage the power distribution between FC and SC. The principle is the same as in ref. [50], but the pre-allocation is done using a virtual potential field algorithm. They conclude that the proposed method can reduce the DC-link

voltage fluctuation and limit the SC SoC range. Xun et al. [52] proposed the same concept as in ref. [51]. The difference is in the input of the virtual potential field algorithm. They use SC voltage and load-current, whereas in ref. [51], they use SC SoC and bus voltage as input for the optimization algorithm. The experimental test shows that the SC SoC is effectively controlled within the desired range.

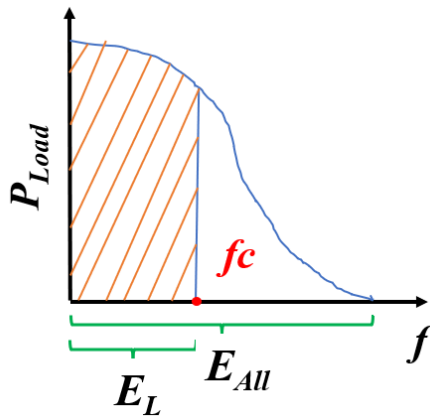


Figure 11. FFT used to vary the cut-off frequency of LPF [50]

3.3.4. Equation-based

Equation-based means the relations between different variables which can be formed as linear or nonlinear functions. Some study uses this method to make the cut-off frequency of the LPF adaptable. Asensio et al. [2] propose an adjustable bandwidth filter as illustrated in Figure 12. Where N is equal to the sampling frequency divided by the cut-off frequency. The larger N means lower bandwidth which uses more power from SC. On the contrary, lower N increases the bandwidth filter which means the battery delivers a large portion of the required power. There are two LPFs used which correspond to N_1 for powering and N_2 for braking. The value of N_1 and N_2 has a linear relation to the SC SoC as in Eq. (3) and Eq. (4), respectively. The experimental validation proves that the proposed method preserves battery

health more effectively compared with the fixed bandwidth filter method.

Nguyen et al. [53] compare some adaptive filtering strategies based on SC variables. Three SC variables as adaptive variables compared are stored energy, SoC, and voltage. The adaptive constant, k_d , is derived from SC using Eq. (5), Eq. (6), and Eq. (7) for energy-based, SoC-based, and voltage-based, respectively. Where v_{sc_min} and v_{sc_mea} is the voltage minimum and measured from SC, respectively. Even though all approach is computed in terms of SC's voltage, they said that each strategy has a different proportion of SC's ability. The block diagram of the proposed system is depicted in Figure 13. From the experimental testing, they conclude that the root mean square (RMS) current of a battery with an energy-based strategy has the lowest value. Moreover, the proposed strategy can be implemented in real-world vehicles.

$$N_1 = (N_{max} - N_{min})SOC_{SC} + N_{min} \quad (3)$$

$$N_2 = (N_{max} - N_{min})(1 - SOC_{SC}) + N_{min} \quad (4)$$

$$k_d = \frac{v_{sc_mea}^2 - v_{sc_min}^2}{v_{sc_min}^2} \quad (5)$$

$$k_d = \frac{v_{sc_mea} - v_{sc_min}}{v_{sc_min}} \quad (6)$$

$$k_d = \left(\frac{v_{sc_mea} - v_{sc_min}}{v_{sc_min}} \right)^2 \quad (7)$$

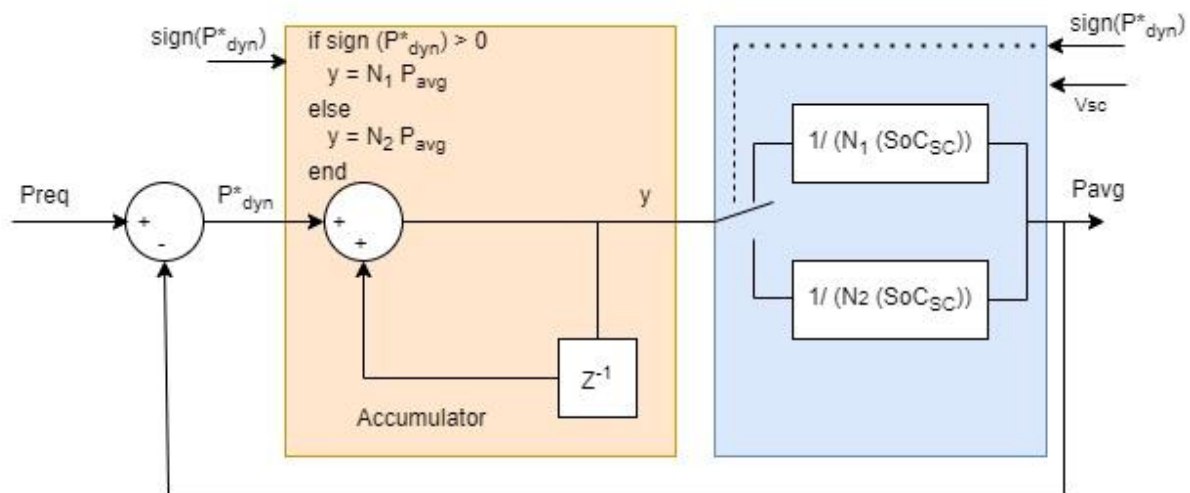


Figure 12. Linear function as adaptif algorithm [2]

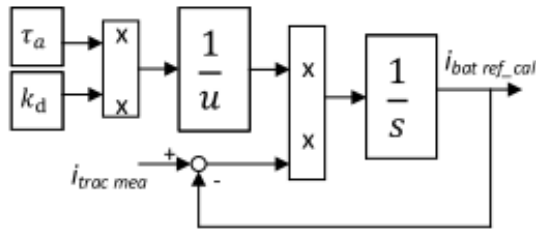


Figure 13. Adaptive cut-off frequency proposed by [53]

Ghoulam et al. [54] proposed adaptive cut-off frequency to manage power distribution between the battery and SC. The cut-off frequency changes based on SC SoC. They also give limits for lower and upper cut-off frequency. The limit is used to protect the SC while maximizing its use. This limit is set based on the highest current step that the system can undergo with a fixed cut-off frequency. The cut-off frequency algorithm is in Eq. (8). Where f_{cLim} and f_{cHlim} is the lower and upper limit of the cut-off frequency. From experimental studies, they conclude that this method can extend the battery's life and allow better protection for SC.

$$f_c = 4(f_{cHlim} - f_{cLim})(SoC_{SC} - 0.5)^2 + f_{cLim} \quad (8)$$

3.4. Combination

Some researchers also combine LPF with other methods to improve its performance. Here, a distinction is made between the adaptive filter and the combined filter. The adaptive filter is mostly used by varying the cut-off frequency of the filter with other methods. On the other hand, the combination means there are two processes, the process in the LPF and the other method which is combined.

Dang et al. [33] also combine LPF and FLC as energy management in an EV with battery and SC power sources. They said that in terms of

extending battery life, fuzzy logic is still limited because it carries many high current change rates which affects the battery life. Therefore, they added LPF to tackle this issue. The fixed cut-off frequency LPF is used where the cut-off value is derived from FFT. After comparing it with another method in a simulation environment, they conclude that the integrated controller has the lowest battery maximum current.

The author in ref. [55] combines the fuzzy and LPF as EMS of an EV with FC and SC power sources as in Figure 14. The input of Mamdani-type fuzzy is power demand (P_{dem}) and SC SoC. While its output is the ratio power assigned to FC. The LPF is used to decrease the fluctuation of FC caused by the transient peak, abrupt acceleration, etc. After simulation, they conclude that the proposed method can smooth the output of FC with robustness and can be implemented in real time. Moreover, it can decrease 19% the current variation.

Salari et al. [56] evaluate the performance of the combination of LPF and FLC of an EV in a Hardware in the Loop (HIL). The ESS uses are battery and SC with only one DC-DC converter on SC's side. The proposed system is shown in Figure 15. The main EMS is the LPF, while FLC is used to ensure the SC is operated in a safe region. Therefore, the input of FLC is a high frequency of the power demand (P_{HP}) and SC SoC. In the end, they conclude that the proposed method can decrease the peak power and battery current by 45.35% and 47.91% respectively.

The authors in ref. [57] combine frequency separation, fuzzy logic, and Lyapunov control for multi-sources EVs. The proposed system uses FC, battery, and SC. The Lyapunov control is used to maintain a constant voltage of the DC-bus. The Mamdani-type fuzzy has the input of load current and the SoC of the battery and SC. Whereas the output is distribution criteria K_d , K_{bat} , and K_{sc} for

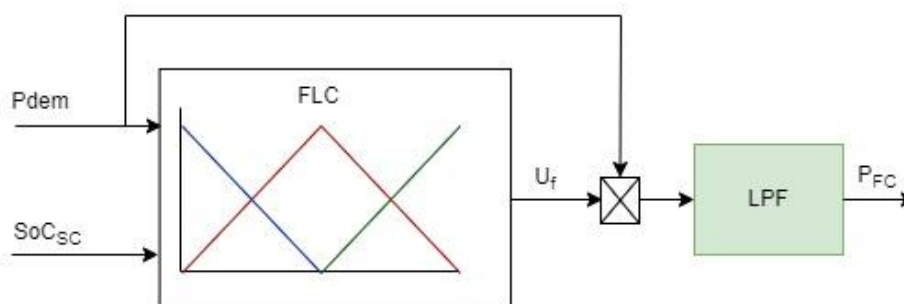


Figure 14. Combine FLC and LPF [55]

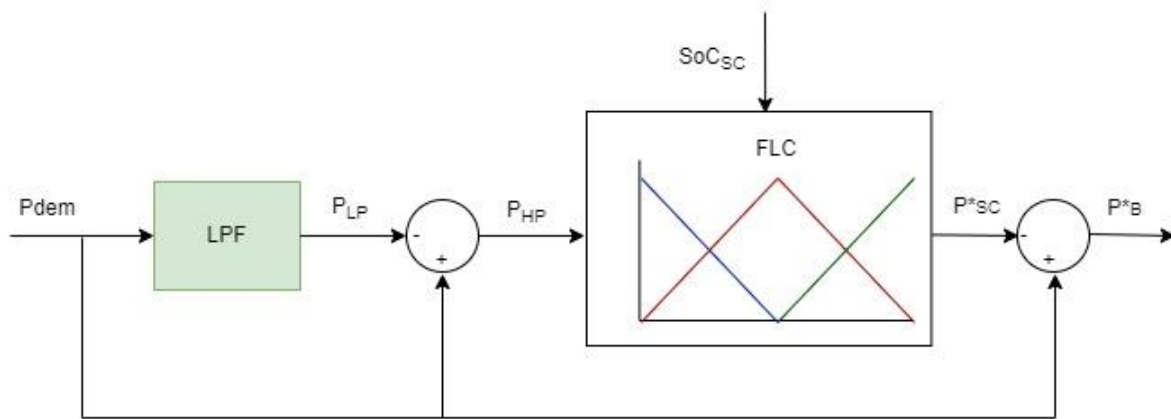


Figure 15. Combine LPF and FLC [56]

fuel-cell, battery, and supercapacitor, respectively. The K_d value is between 0-1 as the proportion for FC, whereas K_{bat} and K_{sc} have the value of 0 or 1 which means charging or discharging, respectively. LPF is used to protect the battery and FC from a strong current dynamic. There are two LPFs for FC and battery. Validated by the simulation, they conclude that each ESS can be used on each frequency range and protected from harmful power dynamics.

Tao et al. [22] combine LPF, FLC, and also wavelet transforms to manage the energy distribution between FC, battery, and SC in an EV. The proposed method is depicted in Figure 16. There are two parts which are adaptive LPF based on FLC, and power-sharing based on Haar wavelet transform (WT). The required power (P_{req}) is sent to LPF and generates low-frequency components for FC and battery (P_{fc_b}). The difference between P_{req} and P_{fc_b} is sent to the SC, whereas the P_{fc_b} is sent to the second part to determine the power allocation for FC and battery. P_{fc_b} is entering the Haar WT which generates P_{fc_ref} , then it is sent to the second FLC including the battery SoC information. The output

of the second FLC is P_{fc} . The P_{bat} is derived from $P_{bat} = P_{req} - P_{sc} - P_{fc}$. They prove the performance of the proposed method both in simulation and experimental. In the end, they conclude that the proposed EMS can save about 7.94% of hydrogen compared to the ECMS (Equivalent Consumption Minimization Strategy) method. Moreover, it can reduce the impact of power fluctuation on FC, extend life spending, and reduce fuel consumption.

Zhang and Li [58] said that frequency separation using LPF may not be sufficient for regulating the peak power demand of the battery. Therefore, FLC is added to mitigate battery peak power. The proposed system is depicted in Figure 17. The power demand enters the LPF and generates power for the SC and battery. The battery power is processed again using FLC to reduce peak power based on delta-SC SoC. If the SC SoC is high, the battery power is reduced which means the battery power from LPF is reduced again which gives excessive power (dP). The dP is added to the SC power reference. After the experimental test, they concluded that the battery capacity fade cost can be reduced.

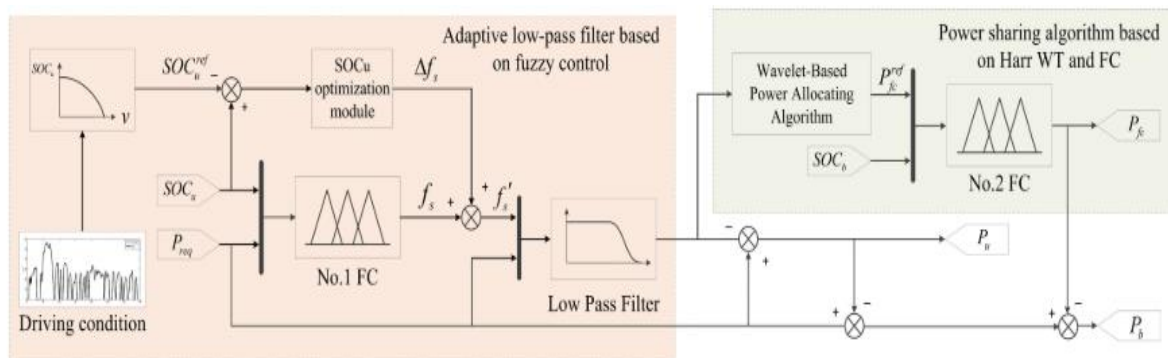


Figure 16. Combine LPF and FLC [22]

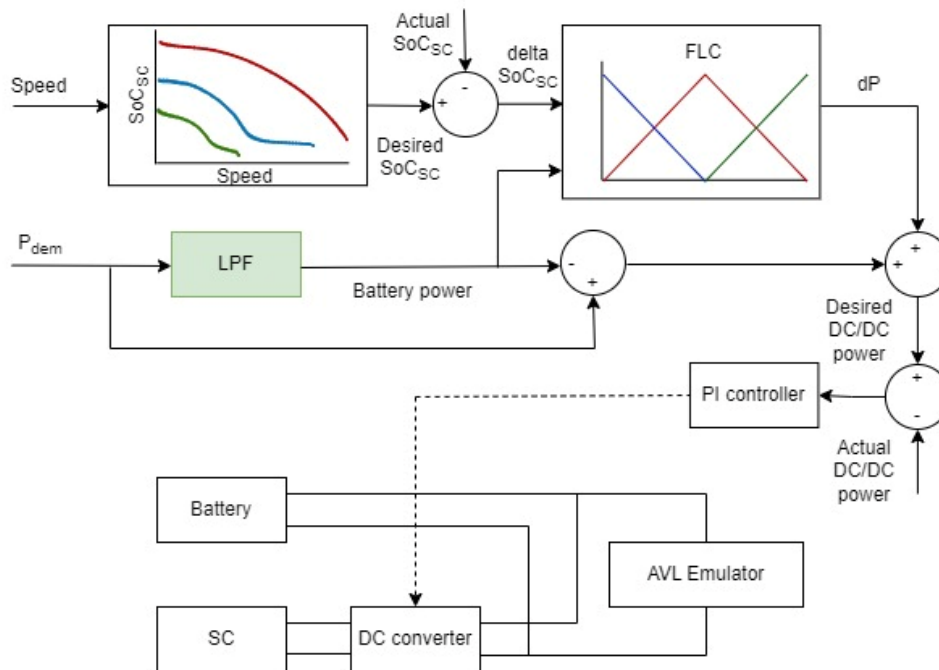


Figure 17. Combine LPF and FLC proposed by [58]

Fu et al. [59] propose a hierarchical energy management strategy that combines Adaptive-LPF and ECMS. The high-layer strategy which consists of adaptive LPF is to adjust SC SoC to supply peak power and recycle braking energy. The lower layer strategy is an ECMS for FC and battery power allocation to reduce fuel economy and extend the lifespan. The adaptive mechanism in LPF is based on SC SoC. Both simulation and experimental studies confirm that the proposed method can effectively manage the energy distribution between the power sources.

The author in ref. [60] combines LPF and power limitation in a HESS EV of battery and SC. Power limitation is used to limit the power from the battery based on its SoC. However, they do not explain clearly how to get the cut-off frequency of LPF. After the simulation verification, they conclude that the proposed system can improve the life of the storage system.

3.5. Discussion

The LPF is a simple EMS algorithm that can be implemented in real time. There are four different ways of implementing LPF which are: fixed cut-off, optimal cut-off, adaptive cut-off, and combination. In the fix-cut-off, there are some methods to get the cut-off frequency the Ragone plot, Fast Fourier Transform (FFT), power spectral density (PSD), analytical method, and trial. Among this method, the Ragone plot is the only

track independent. Whereas the others need track information for the calculation. The Ragone plot method is only based on the energy and power density of an ESS; therefore, the result is general. Whereas the other method which tracks dependent will give better results in the predefined track, but not guarantee the same performance for different drive cycles. The second way is optimal cut-off frequency, where the cut-off frequency is derived from optimization methods such as Dynamic Programming (DP). This method also tracks dependent.

The adaptive cut-off uses the adaptive algorithm to make the cut-off frequency vary based on some determined condition. The methods used are rule-based, fuzzy-based, FFT-based, and equation-based. The first and second method's performance is dependent on the rule used; therefore, the experience of the designer is needed. The FFT-based needs to combine with another method to get the allocation of the power before it is translated to be cut-off frequency. In the equation-based, the relationship between some variables needs to be carefully chosen to get the best performance.

The last way is by combining LPF with another method. In this way, there is a lot of combination of LPF methods proposed by the researcher. Most of them, which the authors can find are in combination with FLC. They use LPF to handle

the transient dynamics of the system. On the other hand, the filter-based method cannot handle the high amplitude of power demand. Therefore, another method is needed to tackle this issue. Another problem is that the LPF EMS principle is dividing the load frequency; therefore, it cannot maintain the SoC of the ESS in a specific range. The EMS should use ESS protection for example SoC protection. Figure 18 resumes the LPF classification in the EMS of EV application.

Compared to the fixed cut-off frequency, the optimal cut-off will give a better result. However, this method is track dependent which cannot guarantee the same performance in the other

track. The adaptive cut-off can handle this issue by varying the cut-off frequency based on the determined condition. Since the LPF method cannot give the SoC protection; therefore, combining it with another method to maintain the SoC of the ESS under the limit is required. Table 2 resume the advantage and disadvantages of different architecture of LPF EMS.

Most of the references discussed using the simulation to prove the performance. Some of them use the HIL method. Only a few of them use experimental in small-scale or prototype vehicles. Therefore, the hardware implementation of the LPF is another challenging spot for the researcher.

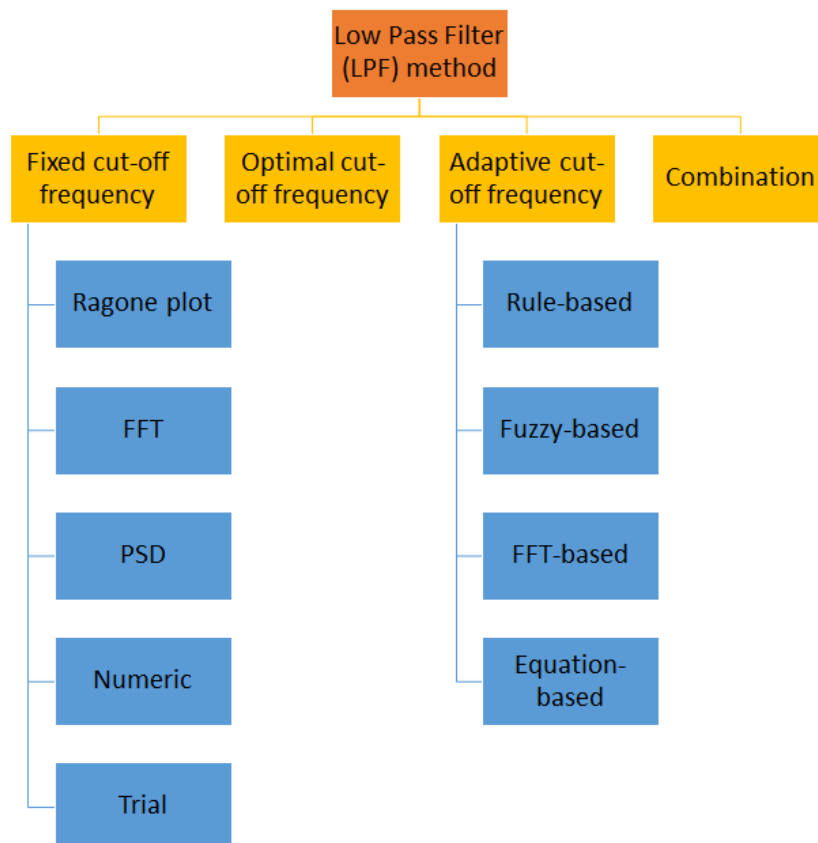


Figure 18. LPF EMS classification

Table 2. The advantages and disadvantages of different architecture class of LPF EMS

Method	Advantages	Disadvantages
Fixed cut-off	Simple, some method tracks independent	Poor performance
Optimal cut-off	Good performance in a specific track	Track dependent
Adaptive cut-off	Track independent	Complex algorithm
Combination	Can be track dependend or independent	Complex algorithm

4. Conclusion

In conclusion, the Low Pass Filter (LPF) emerges as a practical and adaptable Energy Management Strategy (EMS) for Hybrid Energy Storage Systems (HESS) in Electric Vehicles (EVs). This review paper comprehensively explored various approaches to implementing LPFs in real-world applications, drawing insights from a diverse body of literature, including journal articles and conference proceedings.

Four main LPF implementation methods were examined: fixed cut-off, optimal cut-off, adaptive cut-off, and combination. The fixed cut-off method, while simple, falls short in adapting to track changes, whereas the optimal cut-off method excels in specific drive tracks but lacks versatility. On the other hand, the adaptive cut-off method, despite its complexity, offers track-independent adaptability and enhanced performance. Furthermore, the combination method mitigates LPF's limitations, particularly in addressing State of Charge (SoC) constraints.

This article serves as a valuable resource for scholars interested in exploring energy management strategies in EVs, particularly those employing the filtering method. In future work, researchers can delve into the practical implementation and performance assessment of LPFs in real-world applications. Such efforts hold promise for advancing the efficacy of HESS and contributing to the ongoing development of environmentally friendly transportation solutions.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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