

Investigation of High Frequency AC Power Distribution Benefits for the Automobile Auxiliary Electrical System

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ABSTRACT

This paper aims to indicate the advantages and any drawbacks of high frequency alternating current (HFAC) power for vehicle auxiliary electrical systems. Generally, benefits of HFAC include efficient power distribution and transformation, space and weight saving and load galvanic isolation. In addition, HFAC bus topologies are distributed to the point of use, lending the system to easy fault detection. The paper is structured as follows: first, the main findings of the most relevant automotive HFAC studies are outlined. Next, an HFAC architecture is proposed which is compared to the existing 14V and proposed 42V centralised DC networks in terms of power distribution efficiency and wiring harness weight saving. For this analysis, the case study of a medium-sized passenger vehicle is considered, and a group of intermittent and continuous auxiliary loads with a cumulative power of 2.8kW. The calculations over a 1200s drive cycle show that the power distribution efficiency for a 50kHz, 100V AC power bus increases by 90 per cent and 80 per cent compared to 14V and 42V DC topologies, respectively, and the wiring copper weight drops significantly by 70 per cent and 30 per cent, respectively.

INTRODUCTION

The benefits of HFAC power have been investigated since the 1980s for application areas including aerospace, electronic equipment and microgrid power systems [1,2,3,4]. These findings are the key rationales for pursuing an in-depth investigation of HFAC power distribution for vehicle auxiliary electrical systems, and can be summarised as follows:

i). HFAC architectures employ a distributed topology where power converters are allocated at each point of use. This lends the system to a better design and easy fault tracking,

unlike fault tracing in existing vehicle centralised DC networks which can contain up to 600 sub-modules and connectors, 1500 wires and up to 2000 terminals [5].

ii). HFAC architectures benefit from the use of more lightweight and compact components. The high network frequency translates into smaller circuit elements including inductors, capacitors and transformers [6]. In addition, smaller and lighter AC motors operating at 400Hz as in present aircraft electrical systems can be easily interfaced from an HFAC bus and can potentially replace current low torque, constant speed DC motors in pumps, compressors and fans.

iii). AC power transformers have high power conversion efficiency in the region of 97 to 99 per cent, compared to the efficiency of DC/DC converters of 80 to 95 per cent. AC transformers can be used to efficiently interface auxiliary loads to the HFAC bus [7, 8].

iv). Based on the SAE J2232 standard, voltages as high as 120V AC at high frequency are safe in vehicles. This allows for lower current power distribution, thus minimising I^2R losses. In addition, it is noteworthy that current at frequencies higher than 10kHz is safer for human cells than DC current, as shown in Table 1 [9].

Table 1. Relative effect of electric current on human cells and tissues [9]

Frequency [Hz]	DC	10	60	400	1k	10k	more than 10k
Perception and paralyses, relative	0.2	0.9	1	0.7	0.6	0.2	0.01

v). The skin effect causes the high frequency current to flow through a smaller cable area than the one physically available, thus HFAC power has to be distributed using flat cables. Although this arrangement can prove to be more expensive than the DC counterpart, it can contribute

significantly to reducing the wiring harness weight which can reach up to 50kg in medium-class luxury automobiles [5].

vi). AC transformers provide galvanic isolation for the loads connected to the bus. Also, any voltage level can be obtained by appropriately choosing the transformer winding turns ratio.

vii). Power regulation can be achieved simultaneously for all loads connected to the bus through local rectification. This capability can prove to be difficult to secure for some of the proposed dual voltage 14V/42V DC architectures, where only one of the two buses can be regulated at any given time (e.g. dual-stator alternator [10], dual-reference alternator or transformer/rectifier power nets [11]).

viii). New power recovery and generation technologies are making their way into vehicles, such as the integrated-starter generators that capture energy during vehicle deceleration or solar roof power. These novel power sources can be integrated into an HFAC distributed power generation system, following the efficient integration of disparate energy sources onto the same HFAC bus for microgrids [3].

Section two of this paper highlights the advantages and any drawbacks of HFAC power in a vehicle environment, based on the most relevant and representative automotive studies. Next, the case study of an HFAC architecture topology for a medium-size passenger vehicle is presented in section three. In particular, the case study focuses on quantifying advantages in terms of power distribution efficiency and weight saving for the HFAC network topology in comparison to the present 14V DC and proposed 42V DC buses. Section four summarises the findings, draws the conclusions of this analysis and indicates a strategy for future work.

HFAC POWER DISTRIBUTION FOR AUTOMOTIVE APPLICATIONS

The pursuit of HFAC power advantages for the International Space Station (ISS) by NASA and the successful implementation of AC electrical systems in aircraft have sparked the interest of the more conservative and cost-aware automotive industry to follow suit, although not to the same extent. This section describes first the main studies of on-board HFAC power which are illustrative of different voltage and current waveforms, distinct architecture topologies and also indicative of benefits for auxiliary and propulsion electrical loads. The main implications of these findings are included in the second subsection.

STUDIES OF ON-BOARD HFAC POWER

The study carried by Kokes [12] is the only work that focused on the feasibility of a power bus based on square-wave voltage, variable-duty sinusoidal current. This concept, which appears to be the most advanced work into HFAC for vehicles, is summarised in Table 2.

The research focused on the performance analysis of a series oscillatory inverter and on demonstrating the viability of HFAC as power distribution means in vehicles. The experimental setup, which corresponds to the diagram shown in Fig. 1, included a battery-supplied 4kW inverter, four high power consumers acting as 310V DC rectifiers and a front rectifier module producing two outputs of 13V DC and 42V DC. In addition, the battery management module was operated as both AC inverter and DC rectifier, thus allowing energy flow from and to the HFAC bus. It is notable that efficiency higher than 90 per cent was calculated for the inverter and the rectifier modules; nonetheless, the author noted that the no-load power losses for the HFAC setup were higher compared to the resistive losses of 55W of the counterpart DC system.

<table 2 here>

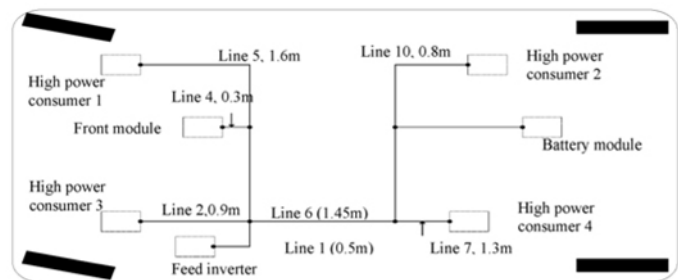


Figure 1. Wiring structure for HFAC experimental setup [12]

A second noteworthy investigation of HFAC power was conducted by Bose et al. [13], which is the only proposition for a high frequency, one-phase sinusoidal AC voltage as power distribution means in a series hybrid electric vehicle. The authors noted that the possible frequency and voltage can be 20kHz and 440V, respectively. The bus concept, which is depicted in Fig. 2, employs a lead-acid battery for energy storage and a gasoline engine for power generation. The battery voltage is inverted by an H-bridge to square wave alternating voltage, which is subsequently filtered by the double LC resonant circuit. Next, the sinusoidal voltage is stepped up with isolation by the high frequency transformer and distributed to the variable voltage, variable frequency converters interfacing the cage-type induction motors and the starter/ generator.

Table 2. Waveform and properties of the HFAC bus concept proposed by Kokes [12]

Inverter name	Current and voltage waveforms	Corresponding voltage and current equations	Bus properties	
BULSI (square wave voltage, sinusoidal current with gaps)		$u_N = \begin{cases} +U_N, 0 < t < \frac{\pi}{\omega} \\ -U_N, \frac{\pi}{\omega} < t < \frac{2\pi}{\omega} \end{cases}$ $i_N = \begin{cases} +I_N \sin(1 + \Delta)\omega t, 0 < t < \frac{\pi}{(1 + \Delta)\omega} \\ 0, \text{otherwise} \end{cases}$	Voltage	80V
			Frequency	25kHz
			Current gap variation factor	$0.1 < \Delta < 0.2$

voltage, variable frequency output of the vehicle alternator, while the bi-directional AC/DC converter charges the battery at 12V and supplies essential loads when the ignition is switched off.

The distribution boxes shown in Fig. 3 fulfill two functions. First, they convert the HFAC power from the main bus into the voltage and current levels required by the loads. Consumers tapping the AC link can be low power, resistive loads such as electronics and bulbs, or high power inductive loads such as electromechanical

Figure 2. Sinusoidal HFAC single-phase distribution system for series hybrid electric vehicle [13]

Amongst the benefits of this system, the authors noted that since the HFAC bus voltage is isolated from the battery voltage, it can be regulated to a higher amplitude which allows for optimum design of converters and machines. In addition, the converters employ zero voltage switching which translates into high power transformation efficiency, higher reliability and lower electromagnetic interference (EMI). Furthermore, a calculation of AC and DC component sizing indicated cost, size and efficiency benefits for the AC system. On the downside, the system requires the addition of the HFAC inverter and a power transformer in comparison to a DC topology. Also, since the converters are transforming high frequency into lower frequency AC, switches S1 to S6 and S1' to S6' in Fig. 2 have to withstand AC voltage and conduct and block current in both directions. Therefore, an equivalent AC switch must be used, which has inverse series IGBTs or MOSFETs and bypass diodes as shown on the same Figure.

The auxiliary electrical system submitted by Kassakian et al. [14] is indicative of the potential of HFAC sinusoids to distribute both power and data on the same bus. The architecture, illustrated in Fig. 3, includes an AC/AC converter which produces 48V at 25kHz from the variable

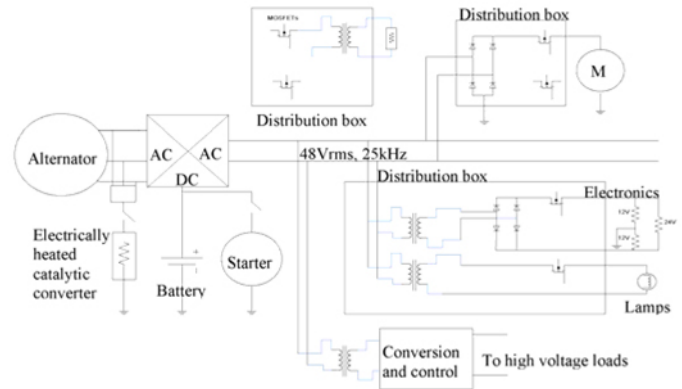


Figure 3. HFAC power and data distribution system [14]

valves or active suspension systems. In either case, HFAC is easily stepped down or up with isolation by power transformers. The second role of the distribution boxes is to be part of a data distribution network that carries control signals according to the power requirement at the user end. The authors exemplify that distribution boxes can be placed at the vehicle rear serving loads such as lights, defrosters, audio systems or can be placed in the glove compartment for

infotainment systems, power windows, door locks or cabin lights.

The electrical networks described so far are based on single-phase AC waveforms at high frequency. A distinct proposal for a vehicle power network is shown in Fig. 4 and it makes use of three-phase sinusoidal AC at 400Hz as in aircraft electrical systems [15, 16]. The third phase adds safety and reliability to the system; should one line fail, the remaining two will ensure the system does not fail completely.

The main components of this power generation subsystem are the alternator, a three-phase rectifier, a battery and inverter which can be either of hard-switched or resonant type. The power is subsequently filtered and distributed to either three-phase or one-phase loads.

Masrur et al. [15, 16] have performed size and cost estimation for possible AC components that can be integrated in the three-phase network of Fig. 4. The analysis concluded that varying the operating frequency from 400Hz, to 800Hz and 1600Hz for the DC/AC inverter at 2kW output has no impact on its size and cost. It was further shown that an overall decrease of approximately 8 per cent in size of optimised one-phase AC motors compared to DC motors is possible, and up to 40 per cent for three-phase induction motors [16]. The machines investigated by this study are detailed in Tables A.1 and A.2, including their operating points (rated speed and torque, output and input power, efficiency) and size (diameter, length and weight). In addition, Table A.1 includes information on the appropriate gear ratios required to interface 400Hz motors for different applications in vehicles.

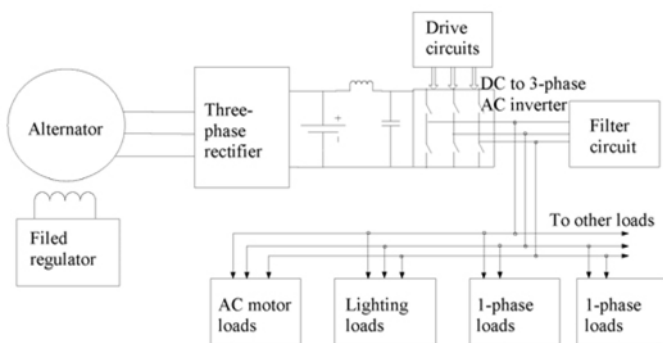


Figure 4. Three-phase AC power distribution architecture [15]

Another interesting result brought forward by this investigation is the estimation of the relationship between AC motor power factor and cost saving, shown in Fig. 5. The key to this plot is the link between the power factor and the wiring harness, the volume of which changes proportionally with the inverse of power factor squared. The Figure shows that the break-even point in savings is for a power factor of

0.737 for the three-phase 400Hz system and 0.956 for the single-phase equivalent. Since the power factor of induction motors is likely to be higher than 73 per cent, it can be inferred that the three-phase system can offer reasonable motor cost savings.

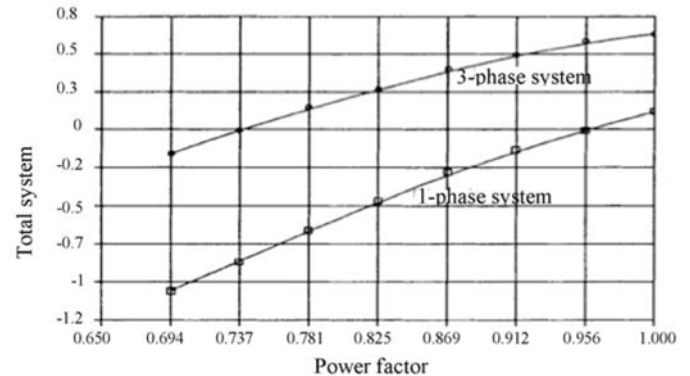


Figure 5. Total normalised cost saving vs. power factor of AC motors [16]

IMPLICATIONS FOR THE VEHICLE ELECTRICAL SYSTEM

The studies presented in this section are illustrative of different topologies proposed for vehicle AC networks, as well as for particular waveforms considered and different frequency and power levels. Apart from sharing the same energy and power source with a DC architecture, an HFAC system is completely different. From a structure point of view, it requires a dedicated one-phase or three-phase DC/AC inverter, power transformers to step the voltage as required by AC loads and rectifiers to interface DC loads. In addition, HFAC power converters utilise two inverse series MOSFETs or IGBTs as basic switching elements. Therefore, the number of components are doubled compared to DC inverters which can potentially represent a reliability issue for AC power regulation modules.

Another distinct feature of an HFAC architecture is that flat cables are preferred for power distribution. Since current distributed at high frequency tends to flow through a smaller conductor area than the one physically available (the skin effect), flat conductors are recommended for HFAC power distribution. Essentially, such cables can be expensive to manufacture and have to be isolated for electromagnetic compatibility with their environment. Nevertheless, as it will be argued in the following section, flat distribution cables are lighter than DC cables for the same power rating and can contribute to the reduction of vehicle mass and improve power distribution efficiency.

It can be argued that from an EMI point of view, sinusoidal voltage and current are a better choice compared to square