Saeed HASANZADEH[1], Sara RANJBAR[1], Mohammad RAJABI-SEBDANI[1]

Department of Electrical Engineering, Harand Branch, Islamic Azad University, Isfahan, Iran (1)

A Proposed Structure for Enhancing the Electric System Availability in an Electric Vehicle

***Abstract**. In electric and hybrid electric vehicles, availability of the electrical system or subsystem is a matter of importance in customer satisfaction point of view. In this paper the system/subsystem availability of multiplexed wiring harness system to the both auxiliary and the propulsion loads are studied and a comparison between its availability and that of a regular non-multiplexed system is conducted. Based on this study a combined structure is introduced. It is deduced from the results, the proposed structure improves availability of the system.*

***Streszczenie.** W artykule analizowane są możliwości rozszerzenia funkcjonalności system elektrycznego w pojazdach hybrydowych. Stwierdzono że systemy z multipleksowaniem umożliwiają znaczną poprawę efektywności systemu. (**Propozycja struktury systemu elektrycznego w pojazdach hybrydowych**)*

Keywords: System Availability, Electric Vehicle, reliability, multiplex system.
Słowa kluczowe: pojazdy elektryczne, systemy elektryczne w pojazdach

Introduction

The automotive industry is currently going through a great increase of electronic equipment for on-board vehicle control. The growth of automotive electronic is the result of customer's demands for better safety and greater comfort. In modern cars, an advanced distribution network connects tens of electronic control units (ECUs) implementing sophisticated real-time control functionality [1-6]. The multiplex network, where multiple nodes are connected by relatively few wires (bus), is the solution which the industry has adopted [2-9]. As the multiplex wiring harness has fewer connectors and wires running through the vehicle in compare to regular hard connected wiring harness, it seems more reliable. However, due to the safety-critical nature of the automotive multiplexing system, considering availability of the system and comparison with other structures are matter of importance.

In the automotive multiplex system, although the wiring harness system complexity is obviously less, some additional components such as the intelligent modules at various load and source locations exist and the overall availability of the subsystems is dependent on the reliability of each of these modules. The availability is also influenced by the intermediate components, the power bus, the communications bus, connectors (at both power and signal levels), and the reliability of the message transmission, particularly during heavy traffic conditions on the communication bus.

Although advantages of a multiplex system are obvious, in [3-4] has shown that overall availability of its subsystems is less than that of a non-multiplex one.

The purpose of this paper is to discuss the availability of the subsystems in an electric vehicle, both multiplexing and non-multiplexing wiring harness.

To benefit from both advantages of multiplex system and availability of subsystems in non-multiplex system, a new combined structure is proposed.

Studying Different Structures and System Load Availability

A. Different Structures

Different structures for the multiplex wiring system exist for possible implementation ring, linear, star, etc. In this paper ring structure, with all the nodes having equal status in terms of operational capabilities is studied which shown in Fig. 1 [3].

The blocks with connection to the communication bus indicate the intelligent nodes for managing the subsystems. These can contain power electronics based switching modules to connect to the subsystems, or these can also use electromechanical relays. In addition, there can be one main circuit breaker or fuse for protecting the whole low voltage system. Additionally, there can be fuses or mini-circuit breakers for protecting the individual load segments. Same methodology applies to the high voltage circuit.

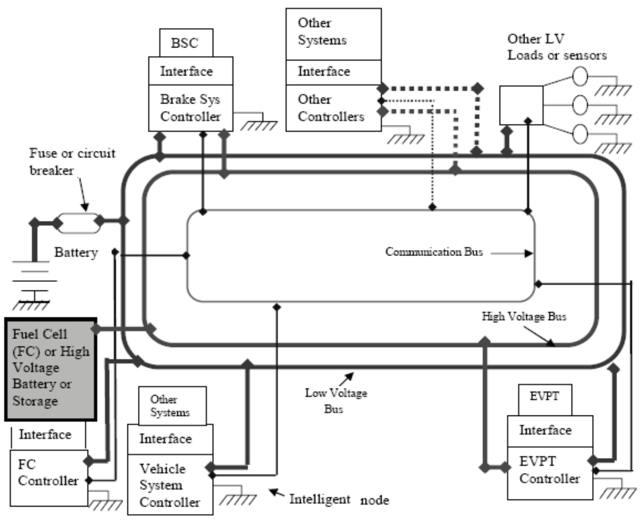

Fig.1. A multiplexed electric vehicle system architecture configuration with power and communication buses, loads, and intelligent nodes for processing communication protocol and load management.

In Fig.1 a few representative subsystem and load items are shown. A typical electric vehicle structure may consist of the following subsystem/loads. High voltage (HV) subsystems: (1) EVPT (Electric Vehicle Power Train) consisting of the induction motor, power electronics, and control, (2) Fuel cell/control, (3) Brake system /control, (4) thermal system/control, (5) Power distribution unit/control, (6) High energy converter, (7) Energy management module. Depending on the vehicle and the structure, the number of such loads can vary. Low voltage (LV) loads related to electric vehicle are: (8) Vehicle system control, (9) LV battery control, (10) Low voltage controller, (11) Refueling module control, (12) Climate control. In addition to these, there are of course other auxiliary loads driven by the low voltage. Therefore there are seven high voltage and five low voltage nodes.

A non-multiplexed system has been shown in Fig. 2 [3]. For an equitable and fair comparison, the same number of subsystems/loads as in Fig. 1 is assumed. However, since there is no soft method of communicating to the nodes anymore, the hard structure for the system as indicated in the Fig. 2 is assumed.

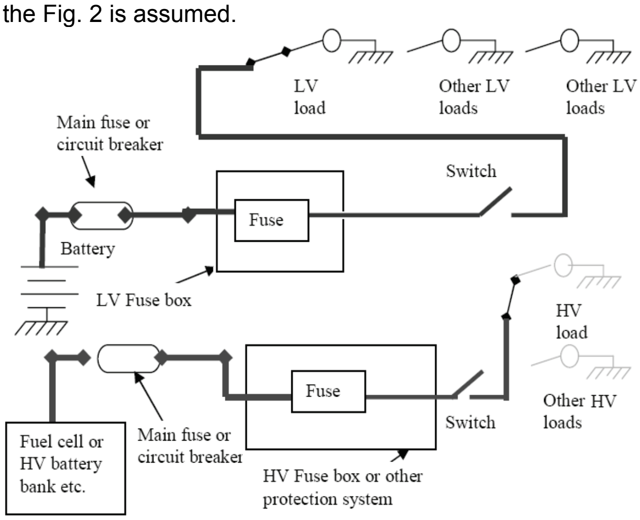

Fig.2. A non-multiplexed electric vehicle system structure configuration.

B. System Load Availability

The final aim of the wiring harness is to actuate or control certain subsystems or loads, based on the information received from the driver and also the various sensors. If this objective fails, the particular subsystem or load will be unavailable. With this in perspective, the following metric is defined [3-4], which is an important figure of merit (or rather demerit, to be precise) indicating how detrimental it is for a particular load/sensor (the *i*-th load/sensor) to be down, by introducing:

$$F_i = C_i H_i (1-\lambda_i) \left\{ \prod_{j=1}^{n} (\lambda_j) \right\} \quad j \neq i \tag{1}$$

Where n is the total number of loads/sensors in the system. In equation (1), λ_i = probability that the i-th subsystem is up or available at a particular moment, which can range from 0 to 1. C_i = criticality of the i-th subsystem, a number which indicates how critical it is for this particular load to be up. A range of 1 to 10 is chosen for convenience, where 1 means not at all critical, to 10 meaning absolutely critical. H_i = times on an average the i-th subsystem is invoked or its status updated during a given time interval (hr, min, sec etc.), a number which will depend on the nature of the load. The term (1- λ_i) indicates the probability of the i-th load being down.

In this equation it is assumed that the probability of more than one subsystem being simultaneously down is of second order, so much smaller, compared to other terms. With the above background, the cumulative system figure of demerit (F_s) can now be defined as:

$$F_S = \sum_{i=1}^{n} F_i \tag{2}$$

Assuming that the total number of subsystems = n. It is noticeable that loads do not imply merely various actuators, lights, etc. they also imply various sensors which are running on their own and communicating with various systems in the vehicle continuously or intermittently.

Proposed Structure

To benefit from advantages of both multiplex and non-multiplex wiring harness system, a combined structure is proposed which has been shown in Fig.3. This system is combination of two aforementioned systems, in which like Fig.1 (multiplex system) there are one communication signal bus and low voltage (LV) power bus, and like Fig. 2 (non-multiplex system) there is one high voltage (HV) power line.

The calculation results, which are presented in next part, show that the proposed structure has better subsystems availability in compare to multiplex system and is close to that of a non-multiplex system. However, in contrast to non-multiplex system it benefits from multiplex system advantages such as accessibility of nodes to the communication signal bus for exchanging data.

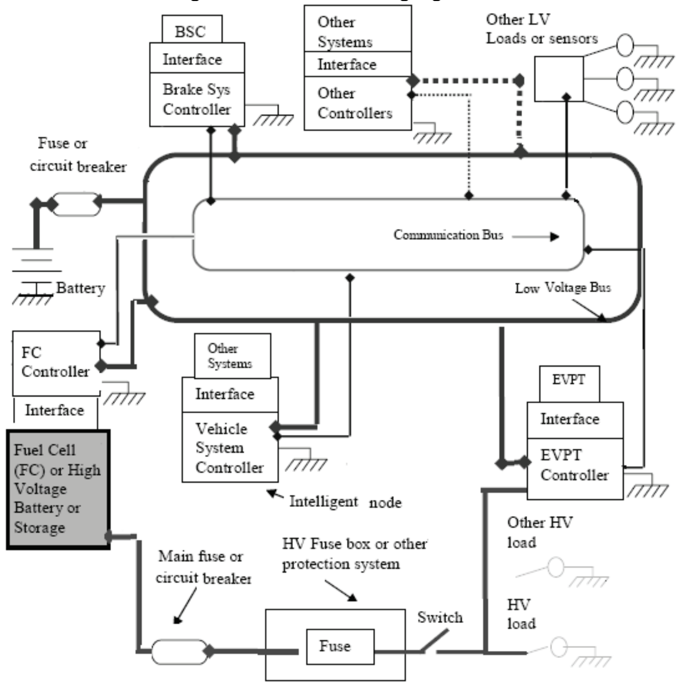

Fig.3. A combined (Mux and non-Mux) electric vehicle system structure configuration.

Availability Calculations of Different Structures

The most important item involved in calculating the cumulative system figure of demerit requires finding the value of λ_i. To calculate this for the multiplex structure which has been shown in Fig. 1, in [3] 22 hard and 2 soft failure items has been considered, each of which can potentially lead to a failure and the availability calculation result has been shown in Table1, and for non-multiplex system which has been shown in Fig. 2, 19 hard failure items has been considered and calculation results have been shown in Table 1.

Here, availability calculation for proposed structure, which has been shown in Fig. 3, is conducted. For an equitable and fair comparison, we will assume the same number of subsystems as in Fig. 1.

The following hard failure items for HV are considered:

1. Fuel cell or HV battery to HV-source cable connector
2. HV source cable to HV main-fuse connector
3. HV Switch to HV-load cable
4. HV Main-fuse to HV fuse-box connector
5. HV Fuse box to fuse connector
6. HV Switch or relay
7. Switch to HV load-cable connector
8. HV load-cable to load connector
9. HV load to ground connector
10. HV load to source return cable

(LV) Hard failure items:

11. LV Battery to battery-cable connector
12. LV Battery-cable to main-fuse connector

13. Main-fuse to power-bus connector
14. LV Power-bus cable
15. LV Power-bus cable to intelligent-node connector (each node consisting of both the power module and also the communication module)
16. Signal-bus (twisted pair etc.)
17. Signal-bus to node connector
18. Node-module
19. Node to LV load-fuse connector.
20. Load-fuse to LV load connector
21. LV Load to ground connector
22. Electromechanical relay or solid-state switches connecting the LV load (can replace the fuse depending on the system).

Soft failure items:
23. Network message overload and/or error at source end (at message initiating node) causing priority based queuing and leading to delay and/or error in transmission10.
24. Failure to win contention with other nodes leading to delay for the message to reach destination, and/or error in message transmission.

It is noticeable that the probability of hard item failure changes with time, starting from infant mortality 11-13 to deterioration with usage and age. For the soft items, the probability of failure will depend on the message loading, message interval in the system, electro-magnetic interference (EMI) among others, and is directly related to the quantity ΣH_i, for i = 1 to k (number of loads).

The reliability of each item (corresponding to the list of 22 hard items and 2 soft items mentioned earlier), is indicated by the symbol ξ, which indicates the probability that a particular item is up (operating properly) at a particular time.

For the hard failure items:

ξ_1 = 0.99999	ξ_2 = 0.99997	ξ_3 = 0.99997
ξ_4 = 0.99999	ξ_5 = 0.99998	ξ_6 = 0.99999
ξ_7 = 0.99997	ξ_8 = 0.99997	ξ_9 = 0.99999
ξ_{10} = 0.99998	ξ_{11} = 0.99999	ξ_{12} = 0.99999
ξ_{13} = 0.99995	ξ_{14} = 0.99999	ξ_{15} = 0.99997
ξ_{16} = 0.99998	ξ_{17} = 0.99997	ξ_{18} = 0.99998
ξ_{19} = 0.99998	ξ_{20} = 0.99995	ξ_{21} = 0.99995
ξ_{22} = 0.99999		

For the soft failure items:

ξ_{23} = 0.99998 ξ_{24} = 0.99998

In the above the paths from the source to loads are traced. For hard LV items, only the items from 11 to 14 in the list of hard failure items given previously will be common to all nodes, and the rest of the items will be separate for each nodes. Similarly, only the items 1 to 4 in the previous list will be common to all HV nodes related with HV.

For the HV and LV loads 7 and 5 of them respectively let us assume the following quantities for C_i and H_i:

C_1 = 10	H_1 = 100	C_2 = 7	H_2 = 20
C_3 = 5	H_3 = 20	C_4 = 5	H_4 = 7
C_5 = 10	H_5 = 20	C_6 = 10	H_6 = 100
C_7 = 8	H_7 = 20	C_8 = 10	H_8 = 100
C_9 = 8	H_9 = 20	C_{10} = 6	H_{10} = 50
C_{11} = 8	H_{11} = 20	C_{12} = 4	H_{12} = 10

The probability that a particular (n-th) high voltage subsystem is available, is given by the product of all the reliability terms ξ_i for i = 1 to 10. Probability that a low voltage load is available is given by the product of all the reliability terms ξ_i for i = 11 to 24, for n = 1 to 7 [10-12]:

$$(3) \qquad \lambda_n = \prod_{i=1}^{10} \xi_i$$

Here, if the values of ξ_i are inserted, we get, for high voltage loads, λ_n = 0.999800017599104, assuming same component reliabilities in each node. Hence we can easily see that whereas the individual component failure probabilities (ξ_i) were chosen to be between 1 to 5 per 100000, after combining all the components together, we get a failure rate of about 20 per 100000. Although this number is quite small, it might still contribute significantly toward the overall system availability or lack thereof. Similarly, for low voltage loads the corresponding equation will be [10-12]:

$$(4) \qquad \lambda_n = \prod_{i=11}^{24} \xi_i$$

It can be seen that this leads to λ_n = 0.999640058694257, for n = 8 to 12, for the low voltage loads. Thus for the low voltage loads the failure probability is 36 per 100000 (equation (4)).

In addition to the above, in general multiple loads can be connected to a single node, particularly for low voltage loads.

This creates a reliability issue, leading to the failure of a subsystem/load cluster, should any one or more of the linkages leading to the particular node fail. This can pose a potentially unacceptable situation [4]. However, we will assume that high voltage subsystems/loads will not be clustered together under the control of one single node.

Figure of demerit for the vehicular system, considering individual subsystem/load failure probabilities, is computed by excluding multiple node failure probabilities, which is of second or higher order. So, during our computation we compute the probability of failure of load # 1 in node # 1, and assume that all the other loads and nodes are available. This leads to, with all the loads taken into account, a cumulative figure of demerit due to individual load failures, to be [10-12]:

$$(5) \qquad F_S = \sum_{k=1}^{12} C_k H_k (1-\lambda_k) \{ \prod_{m=2}^{12} (\lambda_m) \}$$

Where λ_k is the reliability for the k-th load. Inserting all the necessary values, we get from equation (5):

(6) F_s = 0.977894679578

In equation (5), the value of k runs from 1 to 12, 7 for the high voltage loads, and 5 for the low voltage loads. Finally there is the probability of a total system failure due to failure of the hard linkages 1 to 3 for the high voltage system and the hard linkages 11 to 13 for the low voltage system. We will not include the items 4 and 14 for this purpose, because these are the HV and LV cables respectively. These cables can tolerate up to one break or open fault, and can still supply part of the loads in the system, and hence we will not consider these items to lead to a total system failure. This statement, however, does not hold for short circuit faults in the cable.

But this will not significantly affect our conclusion in this paper. Following the same lines of thought as before, for total system failure we get an additional figure of demerit = 0.51221350850. Hence if we add this number to the previous one, the final cumulative system figure of demerit will be:

(7) F_s = 1.4801081880

This is a combination of the figure of demerit due to individual load failures (0.977894679578), and the figure of demerit due to total system failure (0.51221350850). It can be immediately observed that the contribution to the total system figure of demerit comes mostly from the individual load failures, and secondarily from the total system failure. This fact is naturally expected. Since both of these contribute towards the demerit of the overall system. This number can therefore be used as a metric for the purpose of evaluating the quality of a system, and the larger the number, the worse the system availability. Availability calculation results have been shown in Table 1.

Table 1. Comparison between different structures

	Individual Failure	Whole System Failure	Total FS
MUX	2.4330120579	0.3006435575	*2.7336556154*
Non-MUX	0.9687457131	0.3432883206	1.3120340338
Proposed system	0.977894679578	0.51221350850	1.4801081880

As shown in Table 1 the availability of proposed structure subsystems is better than multiplex wiring harness system and close to non-multiplex system. However, as mentioned before, the proposed method, benefits from advantages of multiplex system.

Conclusion

In this paper, availability of multiplex and non-multiplex wiring harness system in an electric vehicle (EV) was studied and showed that the availability of non-multiplex system is better than that of the multiplex system.

To benefit from advantages of two systems new combined structure based on them was proposed. Availability calculation results showed that the proposed structure has better subsystems availability in compare to multiplex system and is close to that of a non-multiplex system. However, in contrast to non-multiplex system it benefits from multiplex system advantages such as accessibility of nodes to the communication signal bus for exchanging data.

REFERENCES

[1] Axelsson J., Efficient Integration of Distributed Automotive Real-Time Systems, *EDA-meeting*, Kista, Sweden, April 11, 2000.
[2] Maryanka, Y., Wiring reduction by battery power line communication, Passenger Car Electrical Architecture (Ref. No. 2000/088), *IEE Seminar 21*, June 2000. 8/1 - 8/4.
[3] Masrur M.A., Garg V.K., Shen J., Richardson P., Comparison of system availability in an electric vehicle with multiplexed and non-multiplexed wiring harness, *VTC IEEE 58th*, 6-9 Oct. 5 (2003), 3277 - 3283.
[4] Masrur M.A., Shen J., Richardson P., Issues on load availability and reliability in multiplexed and non-multiplexed wiring harness system, SAE paper no. 2003-01-1096, *SAE Congress 2003*, Detroit, Michigan, USA.
[5] M.A. Masrur, Digital simulation of an automotive multiplexing wiring system, *IEEE Trans. on Veh. Tech*., 38, No. 3, 140-147.
[6] Masrur M.A., Studies on some alternative architectures for fault-tolerant automotive multiplexing network systems, *IEEE Trans. on Veh. Tech.,* 40 (1991), No. 2, 501-510
[7] Wheat G.C., and Evans W. J., Vehicle Multiplex Wiring – An Implementation, SAE Paper No. 880591.
[8] SAE-SP-1224, Multiplexing, 1997.
[9] SAE-SP-1070, Automotive Multiplexing Technology, 1995.
[10] D. J. Smith, Reliability, Maintainability and Risk, (book), 6th edition, Butterworth Heinemann, 2001.
[11] SAE, Automotive Electronics Reliability Handbook, (book), 1987.
[12] J.H. Derr, C.M. Straub, and S. Ahmed, Prediction of Wiring Harness Reliability, SAE Paper No. 870055.

***Authors**: Saeed Hasanzadeh, PhD student in Electrical Engineering, School of Electrical and Computer Engineering, University College of Engineering, University of Tehran, North Kargar st., Tehran, Iran. P.O.Box: 14395-515, E-mail: shasanzadeh@ut.ac.ir; Sara Ranjbar, Msc student in Industrial Engineering, Department of industrial engineering and Management Systems, Amirkabir university of technology, Email: e.sara.ranjbar@gmail.com; Mohammad Rajabi-sebdani, Msc in Electrical Engineering from university of Tehran, lecturer in Harand university, Email: rajabi_u@yahoo.com.*