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xEV Propulsion System Control-Overview and Current Trends

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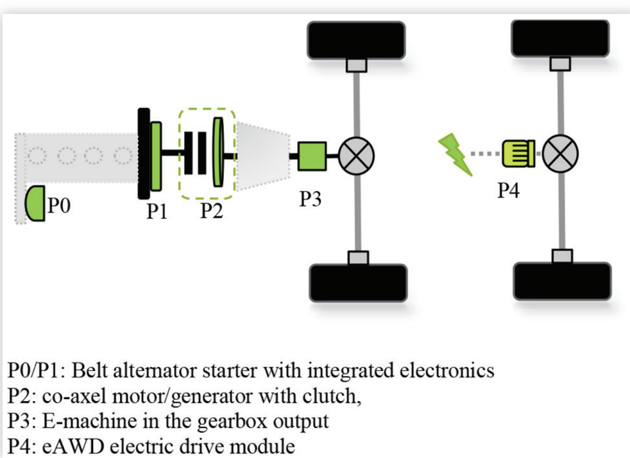
Abstract

Propulsion system control algorithms covering the functional needs of xEV propulsion ('x' donates P0-P4 configurations) systems are presented in this paper. The scope and foundation are based on generic well-established HEV controller architectures. However, unlike conventional HEV (series, parallel and power split) powertrains, the next generation of integrated electric propulsion configurations will utilize a single micro controller that supports multiple control functions ranging from the electric machines, inverters, actuators, clutch solenoids, coolant pumps, etc. This presents a unique challenge to architect control algorithms within the AUTOSAR framework while satisfying the complex timing requirements of motor/generator-inverter (MGi) control and increased interface definitions between software components to realize functional integration between the higher level propulsion system and its sub-systems. This paper lists three areas that system control algorithms typically cover: 1) mode determination and reference command conditioning, 2) serviceability, and 3) safety. Furthermore, this paper focuses on Propulsion Integration Metrics which comprises of control features that impact efficiency, NVH, drivability and performance. Definition of these metrics and specific details of algorithms in these areas are well documented in the literature, and this paper aims to provide current trends and an overview to highlight algorithm interdependence, control architecture, and calibration considerations that impact system level objectives in the context of electrified propulsion. In conclusion, the paper looks ahead to adoption of wide band gap devices (e.g., SiC MOSFETs) in automotive high voltage traction inverters and its potential propulsion system level impact.

Introduction

In recent years, automotive OEMs are making a strategic shift towards an increase in electrified propulsion systems for cost effective compliance with future CO_2 emission standards across vehicle platforms. Figure 1 displays standard xEV powertrain architectures where 'x' refers to the location of electric machine within the context of the powertrain architecture (e.g., P0-P4). As the industry moves towards higher levels of electrical and mechanical hardware integration such as integrated motor-inverter [1] and drive units (e.g. Nissan Leaf, Chevy Bolt, Tesla Model-3), or combine inverter and DC-DC converter from former Delphi Technologies. The sub-components within the electrified propulsion system architecture have associated control algorithms that require higher levels of coordination and interaction to meet a wide set of requirements in performance, hardware protection, functional safety, OBD, efficiency and drivability.

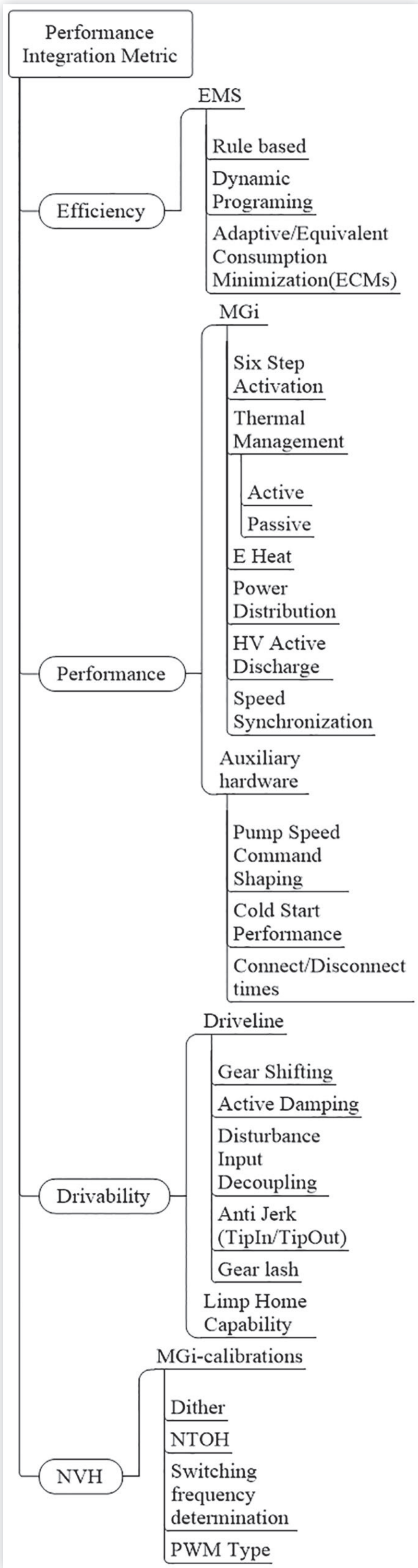
FIGURE 1 xEV powertrain architectures



In conventional architectures, a supervisory controller, also referred to as a hybrid controller, takes on the responsibility of functional distribution between the sub-component features and functions to meet the needs of the entire electrified propulsion system. There are many architectural variants that typically evolve over multiple product generations with many lessons learned captured and designed into the system controls code base.

Conventional AWD system control architectures include multiple sub-components (e.g., shift motors, electromechanical transfer case, couplings) to implement Vehicle Dynamics Control (VDC). Vehicle dynamics control includes algorithms that determine the percentage of torque split between front,

FIGURE 20 EPSC algorithms and calibrations for Propulsion Integration Metrics



Summary

This paper presented a broad framework and rationale for electric propulsion system controls while keeping the scope to electric drives to highlight several key control challenges and associated algorithms that lend to vertical feature integration while maintaining modular software integration concepts to achieve propulsion system performance requirements.

- Using building blocks from well-established traditional HEV controller architecture a context and boundary analogous to a supervisory controller is developed to support Px propulsion architectures.
- Recognize additional control functions taken up by the MCU to support integrated hardware with prefix 'i' and accounting for respective low-level algorithms in iMCU.
- Motor and inverter in the control domain is one component. Control algorithms at system level are dependent on power electronics hardware and controller.
- Consolidation of control algorithms under the umbrella of propulsion integration metrics. Though common knowledge among engineers in respective domains, this paper gives a high-level overview of possible functional integration opportunities in xEV propulsion systems.
- Figure 19 summarizes potential algorithms in the EPSC software component to meet performance requirements for integrated propulsion systems in addition to mode determination, reference conditioning, safety, and services.

In conclusion, looking ahead to future trends with the introduction of silicon carbide (SiC/GaN) FETs for high-speed and high-power application in EV propulsion the scope of improvements in current algorithms, and potential new algorithms, to address challenges and innovate is a critical enabler for product differentiation in a highly cost competitive market. With the advancements in power electronics, close synergies to exploit system level benefits in NVH (with high switching frequency), efficiency (lower switching loss), performance (faster current control bandwidths), and high temperature operation are only starting to be fully explored in a larger context in the automotive industry.

References

1. Jahns, T., and Dai, H., "The Past, Present, and Future of Power Electronics Integration Technology in Motor Drives," *CPSS Trans. Power Electron. Appl.* 2(3):197-216, Sep. 2017.
2. Kiencke, U. and Nielsen, L.," *Automotive Control Systems-for Engine, Driveline and Vehicle*, 2nd Edition", ISBN 3-540-23139-0.
3. Zhu, D. and Pritchard, E., "NCSU Year Three Final Technical Report," SAE Technical Paper 2014-01-2907, 2014, https://doi.org/10.4271/2014-01-2907.

4. Onori, S.,Serrao, L., and Rizzoni, G. ”*Hybrid Electric Vehicles-Energy Management Strategies*”,’ Springer Breifs-Electrical and Computer Engineering- Controls, automation and robotics. ISBN 2191-8112.
5. Dadam, S., Jentz, R., lenzen, T., and Meissner, H., "Diagnostic Evaluation of Exhaust Gas Recirculation (EGR) System on Gasoline Electric Hybrid Vehicle," SAE Technical Paper 2020-01-0902, 2020, https://doi.org/10.4271/2020-01-0902.
6. Rezvani, M., AbuAli, M., Lee, S., Lee, J. et al., “A Comparative Analysis of Techniques for Electric Vehicle Battery Prognostics and Health Management (PHM),” SAE Technical Paper 2011-01-2247, 2011, https://doi.org/10.4271/2011-01-2247.
7. Regulation (EU) 2019/631 of the European Parliament and of the Council of setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. http://data.europa.eu/eli/reg/2019/631/oj 17 April 2019.
8. Treharne, W., Butcher, J., and Sun, X., “System and method for in vehicle resolver alignment”, US Patent, 1048209B2, December 4 2018.
9. Gallert, B., Choi, G., Lee, K., Jing, X. et al., “Maximum Efficiency Control Strategy of PM Traction Machine Drives in GM Hybrid and Electric Vehicles,” in *IEEE Energy Conversion Congress and Exposition (ECCE), 2017* Cincinnati, OH, pp. 566-571, doi:10.1109/ECCE.2017.8095833.
10. Kwon, T., Choi, G., Kwak, M., and Sul, S., “Novel Flux-Weakening Control of an IPMSM for Quasi-Six-Step Operation,” *IEEE Transactions on Industry Applications* 44(6):1722-1731, Nov.-dec. 2008, doi:10.1109/TIA.2008.2006305.
11. Castellazzi, L., Tonoli, A., Amati, N., Piu, A. et al., “Vehicle Driveability: Dynamic Analysis of Powertrain System Components,” SAE Technical Paper 2016-01-1124, 2016, https://doi.org/10.4271/2016-01-1124.
12. Goggia, T., Sorniotti, A., De Novellis, L., Ferrara, A. et al., “Integral Sliding Mode for the Torque-Vectoring Control of Fully Electric Vehicles: Theoretical Design and Experimental Assessment,” *IEEE Transactions on Vehicular Technology* 64(5):1701-1715, May 2015, doi:10.1109/TVT.2014.2339401.
13. De Novellis, L.; Sorniotti, A.; Gruber, P.; Orus, et al. “Direct Yaw Moment Control Actuated through Electric Drivetrains and Friction Brakes: Theoretical Design and Experimental Assessment”. *Mechatronics*, 2015, Vol. 26: pp. 1-15. doi.org/10.1016/j.mechatronics.2014.12.003
14. Arnett, M., Rizzoni, G., Heydinger, G., Guenther, D. et al., “Implementation of an Electric All-Wheel Drive (eAWD) System,” SAE Technical Paper 2008-01-0599, 2008, https://doi.org/10.4271/2008-01-0599.
15. Velazquez, A., “Investigation & Development of Vehicle Dynamics Control Frameworks for an Electric All-Wheel-Drive Hybrid Electric Vehicle” Ph.D thesis, Mechanical & Aerospace Engineering Department, University of California, Davis, 2017.
16. Fan, Y., Li, D., and Crolla, D., “Integrated Vehicle Dynamics Control —State-of-the Art Review,” in *2008 IEEE Vehicle Power and Propulsion Conference*, Harbin, 2008, pp. 1-6, doi:10.1109/VPPC.2008.4677809.
17. He, S., “NVH Design, Analysis and Optimization of Chevrolet Bolt Battery Electric Vehicle,” SAE Technical Paper 2018-01-0994, 2018, https://doi.org/10.4271/2018-01-0994.
18. Hao, D., Zhao, C., and Huang, Y., “A Reduced-Order Model for Active Suppression Control of Vehicle Longitudinal Low-Frequency Vibration,” *Shock and Vibration*1-22, 2018, doi:10.1155/2018/5731347.
19. LIU, X., WU, Z., LU, J., and XU, J., “Investigation of the Effect of Rotation Speed on the Torsional Vibration of Transmission System,” *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 13, doi:JAMDSM0079.10.1299.
20. Son, Y., Welchko, B., Simili, D., Momen, M. et al. “Method and Apparatus for controlling an electric machine”, US Patent application 20170077854, March 16, 2017.
21. Simili, D. and Ballal, S., “Determination of demagnetization torque capability in real time for electric motor in propulsion system”, US Patent 10608567, March 31, 2020.
22. Hwang, S., Lee, J., Kim, K., and Choi, C. “Compensation of Analog Rotor Position Errors Due to Nonideal Sinusoidal Encoder Output Signals,” in *2010 IEEE Energy Conversion Congress and Exposition*, Atlanta, GA, 2010, pp. 4469-4473, doi:10.1109/ECCE.2010.5618432.
23. Wellmann, T., Govindswamy, K., and Tomazic, D., “Impact of the Future Fuel Economy Targets on Powertrain, Driveline and Vehicle NVH Development,” *SAE Int. J. Veh. Dyn., Stab., and NVH* 1(2):428-438, 2017, doi:10.4271/2017-01-1777.
24. Cao, W., Wang, F., and Jiang, D., “Variable Switching Frequency PWM Strategy for Inverter Switching Loss and System Noise Reduction in Electric/Hybrid Vehicle Motor Drives,” in *Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, 2013, pp. 773-780, doi:10.1109/APEC.2013.6520297.
25. Patel, N., Anwar, M., Hiti, S., Welchko, B. et al. “Method and system for operating a motor to reduce noise in an electric vehicle,” US patent application 0298785 A1, December. 4 2008.
26. Jiang, D. and Wang, F. “Variable Switching Frequency PWM for Three-Phase Converter for Loss and EMI Improvement,” in *Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Orlando, FL, 2012, pp. 1576-1583, doi:10.1109/APEC.2012.6166030.
27. Elrayyah, A. and Sozer, Y. “Effective dithering technique for EMI reduction in three phase DC/AC inverters”. Conference Proceedings-IEEE Applied Power Electronics Conference and Exposition-APEC. 2401-2406. doi:10.1109/APEC.2014.6803639.
28. Firdous, A., Imran, M. and Shaik, M. “Analysis of Three Phase Inverter Using Different PWM Techniques”. In: Garg, A., Bhoi, A., Sanjeevikumar, P., Kamani, K. (eds) *Advances in Power Systems and Energy Management. Lecture Notes in Electrical Engineering*, vol 436. Springer, Singapore. doi:10.1007/978-981-10-4394-9_51.
29. Han, D., Li, S., Lee, W., and Sarlioglu, B. “Adoption of Wide Bandgap Technology in Hybrid/Electric Vehicles-

Opportunities and Challenges," in *IEEE Transportation Electrification Conference and Expo (ITEC)*, Chicago, IL, 2017, pp. 561-566, doi:10.1109/ITEC.2017.7993332.

30. Zhang, H., Tolbert, L., and Ozpineci, B., "Impact of SiC Devices on Hybrid Electric and Plug-In Hybrid Electric Vehicles," *IEEE Transactions on Industry Applications* 47(2):912-921, March-April 2011, doi:10.1109/TIA.2010.2102734.
31. Morya, A., Gardner, M., Anvari, B., Liu, L. et al., "Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges," *IEEE Transactions on Transportation Electrification* 5(1):3-20, March 2019, doi:10.1109/TTE.2019.2892807.
32. Reimers, J., Dorn-Gomba, L., Mak, C., and Emadi, A., "Automotive Traction Inverters: Current Status and Future Trends," *in IEEE Transactions on Vehicular Technology* 68(4):3337-3350, April 2019, doi:10.1109/TVT.2019.2897899.
33. Wang, F., and Zhang, Z., "Overview of Silicon Carbide Technology: Device, Converter, System, And Application," *CPSS Transactions on Power Electronics and Applications* 1(1):13-32, Dec. 2016, doi:10.24295/CPSSTPEA.2016.00003.

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Definitions/Abbreviations

AWD - all-wheel drive
HEV - hybrid electric vehicle
OBD - On-board diagnostics
VDC - vehicle dynamics control.
BMS - battery management system
TCM - transmission control module
ECU - engine control unit
SOC - state of charge
HEV - hybrid electric vehicle
EPSC - electric propulsion system control
NVH - noise, vibration, and harshness
AUTOSAR - automotive open source architecture
OEM - original equipment manufacture
NVM - non- volatile memory
WLPT - worldwide harmonized light vehicle test procedure
EMI - electromagnetic interference
PWM - pulse width modulation
ASIL - automotive safety integrity level
WBG - wide band gap
RTE - run-time environment
PWM - pulse-width modulation
SOC - state of charge

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