

Control System Operational Protocol for Dual DC Electric Motor Configuration in Electric Vehicles

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Abstract

This paper is focused on the analysis of the performance of DC electric motor for electric vehicles (EV) in urban and intercity routes. The paper analyzes the different driving conditions in both types of routes reproducing the most current situations and how they influence the electric motor performance. The study is focused on a dual electric motor configuration, series and parallel, which equips an electric vehicle prototype, evaluating the power response using both configurations, and comparing results from any of the two types of DC electric motor. A control system is proposed to commute between series and parallel configuration depending on driving conditions and type of route to maximize the performance of the electric motor. Driving routes have been segmented into five categories, acceleration, deceleration, constant velocity, ascent and descent, as representative of any urban or intercity routes. A simulation process has been carried out to reproduce real driving conditions. The simulation has been applied considering the turning speed of the electric motor as the key parameter to decide which configuration should be selected. The results of the simulation process indicates that the control system selects the working configuration depending on the turning speed of the electric motor but also on the acceleration rate.

Keywords: Electric vehicle, DC electric motor, Dual series/parallel configuration, Control system, Performance improvement

INTRODUCTION

In past years, the promotion of the electric vehicle in the private transportation sector has become a very popular action [1–5], which today is gaining popularity and adepts [6–19]. In city routes the use of the electric vehicle does not represent a serious problem since the distances are relatively short and the EV autonomy is, in most of the cases, enough to cover this distance [20–26]. Nevertheless, car manufacturers continue searching for higher performance of the EV, with the goal of gaining the consumers market and increase the selling of their models. To do so, the research on battery and motor performance has deserved the attention of R&D departments in many cars manufacturing companies as well as in public and private institutions [27–35].

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Received Date: February 14, 2022

Accepted Date: February 24, 2022

Published Date: March 02, 2022

Citation: C. Armenta-Déu. Control System Operational Protocol for Dual DC Electric Motor Configuration in Electric Vehicles. Journal of Mechatronics and Automation. 2021; 8(3): 1–14p.

The increase in EV autonomy, one of the main worries of car drivers, depends not only on the battery capacity, but also in the managing way of the driving and the motor performance of the electric vehicle [36, 37]. The improvement of this latter represents a challenge because of the specific characteristics of the electric motors once they have been installed in the EV; therefore, a deeper analysis of the electric motor performance should be done to increase the motor efficiency, thus enlarging the driving range of the electric vehicle with a more efficient use of the energy.

Electric vehicles can be equipped with continuous or alternate current motors depending on the configuration and manufacturer selection. Direct current motors operate with a type of current compatible with that generated by supercapacitors, batteries and fuel cells, in addition to photovoltaic panels in case this is an alternative source of energy. Alternating current motors need a conversion system, inverter or converter, to take advantage of direct current from any of these sources. Both have advantages and drawbacks, therefore there is not a unique option for the electric vehicle motor system [38–42].

DC motors can be classified into two categories, series wound and shunt wound; among alternating current motors there are different types, magnetic induction motors, permanent magnet synchronous motors, magnetic induction synchronous motors, magnetic induction asynchronous motors and magnetic reluctance motors.

Alternate current motors require a DC/AC converter to adapt the extracted current from the battery to the motor configuration; continuous current motors do not need from this converter but suffer from a lower operating voltage that imposes working at higher electric current level, which are the responsible of the major fraction of energy losses. This drawback has been progressively solved with the development of more powerful motors that operate at higher DC voltages, reducing the electric current, consequently, the energy losses. This reduction means an apparent but effective improvement in the motor efficiency that enlarges the driving range.

Although the current trend is to use alternating current motors, the difference between this type of motor and one with brushless direct current is practically nil; on the other hand, the use of one or another type of motor, AC or DC, is a function of the power, the type of vehicle and the performance, acceleration, maximum speed, consumption, etc., required by the electric vehicle. Likewise, the type of engine is linked to the type of transmission the vehicle is equipped with, although conventional systems are not used in an electric vehicle.

The goal of this paper is the optimization in the managing of the power demand from the battery to the electric motor, fulfilling driving conditions requirements and making the use of energy more efficient, thus having an extended driving range for the electric vehicle.

THEORETICAL BACKGROUND OF ELECTRIC MOTORS

Although there are multiple types of motors, the number of configurations that can be given when it comes to electric vehicles is limited. Electric motors for vehicles are combined, today, with inverters and electronic control systems that allow varied combinations among which are a wide speed range with constant torque and extended speed range with constant power; therefore, depending on the configuration of the propulsion system, the design and type of electric motor will be different.

DC electric motors used to operate at lower voltage than AC motors; this situation has been solved in recent years with advanced configuration that make the DC electric motor operating at voltages closer to the ones of AC motors.

Basically, there are two types of configurations for the mode of operation of a direct current electric motor, series and parallel. The electric motor with brushes in series has the following characteristics, high torque and low speed; these characteristics make it ideal for starter systems. The brush system creates a permanent magnetic field that generates a flux that causes the moving part of the motor to rotate, thus creating a rotational movement that is transferred to the motor shaft.

In general, the torque of a motor can be obtained from the following equation:

$$T_{ax} = T_m G_{R_r} G_{R_{dif}} \eta_{tr} \eta_{dif} \quad (1)$$

Where T_{ax} is the torque at the axis, T_m the torque of the motor, G_R is the gear ratio, and η the efficiency, with tr for the powertrain and dif for the differential. Nevertheless, most electric cars do not have a gearbox nor a differential; therefore, $T_{ax}=T_m$.

The torque of a motor is directly related to its driving force through the expression:

$$F_m = T_m / R \quad (2)$$

Where F_m is the driving force, and R is the wheel radius.

Driving force in an electric vehicle, like in any other car, is composed of four different terms, acceleration, drag force, rolling force, and tangential weighing force. Mathematically:

$$F_m = ma + \kappa v + (\mu \pm \tan \alpha) mg \quad (3)$$

Where m is the mass of the electric vehicle, a is the acceleration, κ is the drag coefficient, v the vehicle speed, μ the rolling coefficient between tires and road, and α the slope of the road, positive for ascent and negative for descent.

Combining equations 2 to 3:

$$T_m = R [ma + \kappa v + (\mu \pm \tan \alpha) mg] \quad (4)$$

Since the mass of the vehicle is also constant:

$$T_m = mR [a + (\kappa/m)v + (\mu \pm \tan \alpha) g] = mR (a + a_d + a_g) \quad (5)$$

Where $a_d = (\kappa/m)v$ is the drag acceleration, and $a_g = (\mu \pm \tan \alpha)g$ is the acceleration required to compensate for the loss of speed in ascent segments of a road.

Grouping all acceleration in one, the torque is expressed as:

$$T_m = mR a_{eff} \quad (6)$$

Where a_{eff} is the effective acceleration corresponding to a specific torque, which is always higher than the real acceleration of the vehicle, a , since the effective acceleration takes into account all driving conditions.

Power consumption is directly related to the torque through the expression:

$$P_t = T_m \omega \quad (7)$$

Where ω is the rotation speed of the electric motor.

Electric motors are able to deliver the maximum torque no matter the driving conditions; therefore, if the effective acceleration increases, the torque does as well and vice versa.

Driving routes in modern urban areas can be considered as a set of three types of segments, flat terrain, ascent and descent; these segments must be combined with acceleration, deceleration and constant speed (cruising) processes, leading to different driving conditions.

In general, when the electric vehicle is running at constant speed in flat terrain, the effective acceleration can be expressed as:

$$a_{eff} = (\kappa/m)v + \mu g \quad (8)$$

Since the inertial acceleration and the slope of the road are null.

In these conditions, the torque and the power are given by:

$$T_m = mR[(\kappa/m)v + \mu g] = (R\kappa)v + mR\mu g \quad (9)$$

$$P_t = mR\omega[(\kappa/m)v + \mu g] = (R\omega\kappa)v + mR\omega\mu g \quad (10)$$

Since the electric vehicle speed, v , is directly related to the turning speed of the electric motor [43], equation 10 can be transformed into a quadratic equation of the type:

$$P_t = a\omega^2 + b\omega + c \quad (11)$$

Where $a=R\kappa r_t$, $b=mR\mu g r_t$ and c is the fitting coefficient, which is currently defined from the adjusting tests.

Assuming the drag and rolling coefficients are constant, and because the rotation speed uses to be constant, the torque depends linearly on vehicle speed, as reflected in equation 9, and the power does as well (see equation 10).

Performance of a DC electric motor

Figure 1 shows the torque and power evolution of series and parallel DC electric motor with the turning speed for equal maximum delivered torque and power.

DC electric motor performance has been divided into five zones, A to E, in Figure 1, corresponding to the torque and power evolution at very low, low, medium, high and very high turning speed range of the electric motor, respectively. Focusing the attention into the power evolution we realize that series and parallel configuration shows the same torque performance in zone A, but with higher rate for the parallel configuration. In zone B while the series configuration maintains the maximum value of the attained torque, parallel configuration shows a continuous linear decline in the torque evolution. The power evolution in this zone B shows a higher performance for the parallel configuration, especially at the half starting interval of the range.

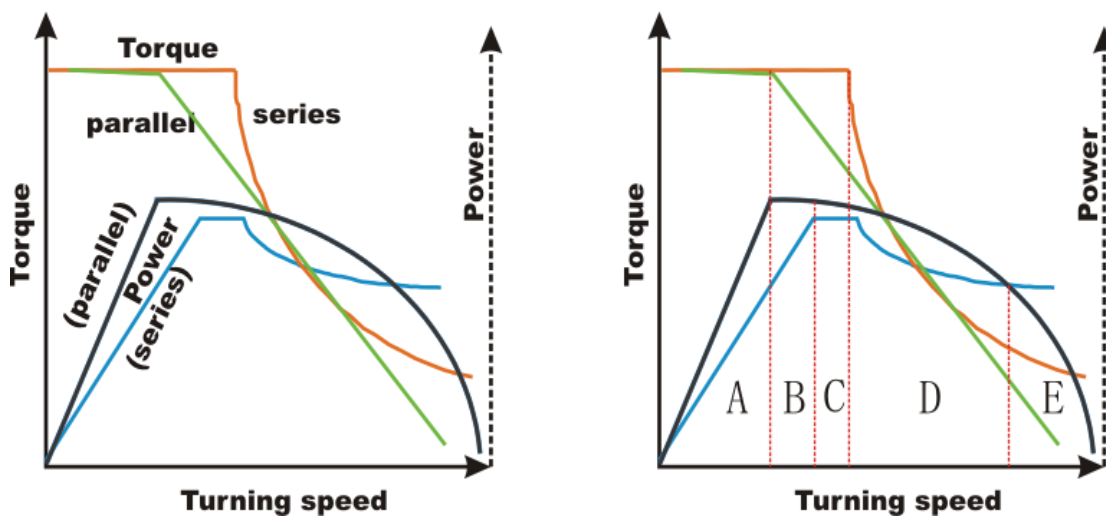


Figure 1. Comparative performance of torque and power for series and parallel configuration of a DC electric motor.

In zone C power from series configuration is very close, in value, to the parallel configuration, although a slight difference in favor of this latter configuration. Torque, however, is higher in the series

configuration showing a constant value for the entire range while in the parallel configuration the linear decline continues.

Torque in zone D slightly differs from series to parallel, even if the series configuration evolves quadratically with turning speed while parallel continues with the linear evolution; nevertheless, the difference in supplied torque in the entire range is of small value and from practical point of view can be considered negligible.

Power in zone D, however, shows an opposite trend in the quadratic evolution of the power with turning speed; parallel configuration provides higher power than series.

In zone E, the observed trend in power evolution for series and parallel configuration continues but enlarging the difference in supply power between parallel and series configuration. On the contrary, series configuration provides higher torque values at very high turning speed, with similar values for both configurations at the first part of the turning speed range.

Maximum value of torque and power shown in Figure 1 can be updated to driving conditions, increasing or decreasing the set-up value; besides, the different sections of the Figure 1 can be combined depending on the driving route conditions and way of driving; in other words, the sequence does not mandatorily follow the represented sequence and can be alternate in a different way.

Considering the driving urban route in a typical day consists of a series of segments that can be associated to the following five categories, acceleration or deceleration process, constant speed running, ascent and descent route, and applying the five selected zones in Figure 1 to these categories, it results:

- A-zone can be associated to the acceleration process, especially when the vehicle starts moving from stopping at a traffic light or traffic jam
- B-zone is typical of the ascending route segment where electric engine requires maximum power and constant torque to push up the vehicle to maintain speed
- C-zone could correspond to cruising segment, since in this condition the vehicle may require increasing the power to compensate the drag force of the wind if the speed is high, or to reduce power requirements in case the speed is low. In both situations the torque reduces considerably due to the inertial effects
- D-zone can be associated to the descending route segment where vehicle tends to increase velocity due to the conversion of potential energy into kinetic, thus reducing drastically the torque and power requirements
- E-zone represents a very unusual driving situation with the electric motor turning at maximum rotation speed and the electric vehicle attaining its maximum velocity

The performance of the DC electric motor can be modeled through a simulation process, obtaining the corresponding coefficients, a , b and c from equation 11. To do so, the DC electric motor should be submitted to specific driving conditions reproducing the real situation in urban and/or intercity routes.

Performance simulation

A simulation process has been carried out in an electric motor of 60 kW of maximum power, which is a current value in modern electric vehicle of high driving range [44]. The simulation has been developed for the above specific maximum power as a function of the turning speed of the electric engine; series and parallel configuration have been used. The simulated electric vehicle characteristics have been:

$$R = 0.245 m; r_t = 10^{-5}; m = 1800 kg \quad (12)$$

And the road condition characteristic parameters are:

$$\kappa = 0.17; \mu = 0.15 \quad (13)$$

The results from the simulation process are shown in Figure 2.

To fairly compare the performance of series and parallel configuration of the DC electric motor, identical maximum power and torque have been considered for the simulation process, as reflected in the graph representation of Figure 1. In such conditions, the performance of the electric motor can be linked to the value of the delivering power for every turning speed.

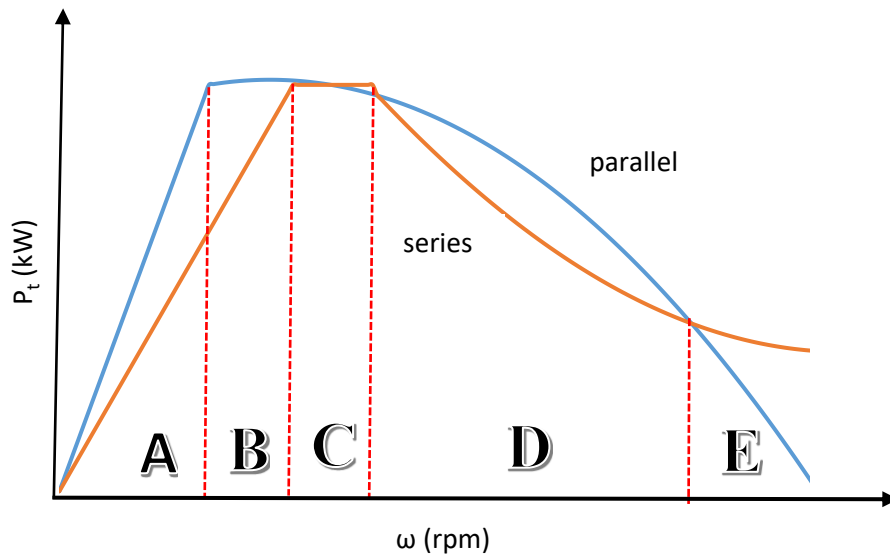


Figure 2. Power evolution for series and parallel configuration of a DC electric motor from the simulation process.

The simulation process has resulted in a power evolution that reproduces the expected evolution of the performance of the DC electric motor (Figure 2) for the two configurations, series and parallel. We realize that the evolution can be fitted to a right line for both, series and parallel, in zone A, to a linear evolution for the series configuration in zones B and C, to a quadratic evolution for the parallel configuration in zones B through E, and to a quadratic evolution for the series configuration in zones D and E. The mathematical algorithms of the fitting process have been presented in the following set of equations:

a) Zone A

$$\begin{aligned} P_t &= 0.0116\omega \quad (R^2 = 1) \text{ (series)} \\ P_t &= 0.0181\omega \quad (R^2 = 1) \text{ (parallel)} \end{aligned} \quad (13)$$

b) Zone B

$$\begin{aligned} P_t &= 0.0116\omega \quad (R^2 = 1) \text{ (series)} \\ P_t &= -4 \times 10^{-7} \omega^2 - 0.0038\omega + 49.954 \quad (R^2 = 1) \text{ (parallel)} \end{aligned} \quad (14)$$

c) Zone C

$$\begin{aligned} P_t &= 57.890 \quad (R^2 = 1) \text{ (series)} \\ P_t &= -4 \times 10^{-7} \omega^2 - 0.0038\omega + 49.954 \quad (R^2 = 1) \text{ (parallel)} \end{aligned} \quad (15)$$

d) Zone D

$$\begin{aligned} P_t &= -3.8 \times 10^{-7} \omega^2 + 0.0038 \omega + 60.505 \quad (R^2 = 1)(series) \\ P_t &= -4 \times 10^{-7} \omega^2 + 0.0038 \omega + 49.954 \quad (R^2 = 1)(parallel) \end{aligned} \quad (16)$$

e) Zone E

$$\begin{aligned} P_t &= -3.8 \times 10^{-7} \omega^2 + 0.0127 \omega + 63.340 \quad (R^2 = 1)(series) \\ P_t &= -4 \times 10^{-7} \omega^2 + 0.0038 \omega + 49.954 \quad (R^2 = 1)(parallel) \end{aligned} \quad (16)$$

Applying data to equation 12, we obtain: see Table 1.

Table 1. Results from the simulation process for the power evolution of the DC electric motor performance.

Configuration		Series		Parallel	
Zone	Value	$a (\times 10^{-7})$	$b (\times 10^{-3})$	$a (\times 10^{-7})$	$b (\times 10^{-3})$
A	Th.	---	11.2	---	20.4
	Sim.	---	11.6	---	18.1
	Dev. (%)	---	3.1	---	12.9
B	Th.	---	11.2	-4	3.7
	Sim.	---	11.6	-4.165	3.8
	Dev. (%)	---	3.1	4.1	2.6
C	Th.	---	1.000	-4	3.7
	Sim.	---	1.036	-4.165	3.8
	Dev. (%)	---	3.6	4.1	2.6
D	Th.	-4	3.7	-4	3.7
	Sim.	-3.8	3.8	-4.165	3.8
	Dev. (%)	5.0	2.6	4.1	2.6
E	Th.	-4	11.4	-4	3.7
	Sim.	-3.8	12.7	-4.165	3.8
	Dev. (%)	5.0	10.2	4.1	2.6

Legend: Th: theoretical; Sim: simulation

Comparing theoretical values and simulation results we can observe the close agreement in the predicted values within 93% of accuracy.

Application of DC electric motor performance to driving conditions

To set up an appropriate control of the DC configuration for an optimum efficiency if the electric motor it is necessary to combine the previously selected zones with the kind of driving, which can be classified in three different categories, aggressive, moderate and gentle. These three types of driving are characterized by the acceleration rate, 2.5 m/s² for the aggressive mode, 1.75 m/s² for the moderate one, and 1 m/s² for the gentle.

Since the acceleration process requires an increasing power supply, zone A for the parallel configuration and zones A and B for the series one, are the most appropriate to fulfil this requirement; acceleration occurs either at the starting up of the vehicle from stopped situation, during ascent if vehicle speed is maintained, or in case of increasing the velocity at the cruising operating mode. On the other hand, the power demand is higher in the aggressive mode.

If the acceleration occurs at low turning speed of the electric motor, parallel configuration should be selected as default option, especially if the cruising mode is reached within a short time; however, if the acceleration mode is maintained for a longer time, attempting to reach higher velocity, a wider range of constant torque is required, what implies the use of the series configuration; the control system should then switch from parallel to series if the acceleration is maintained beyond the set up threshold corresponding to the boundary between zones A and B. This threshold obviously depends on the type

and model of electric vehicle, but it can be configured in the control system software from the technical information provided by the manufacturer.

Cruising mode currently corresponds to medium and high turning speed values, requiring a low power demand because of the dynamic driving conditions, null acceleration; the cruising mode, however, requires increasing power if vehicle speed is increased to compensate the higher drag force. This situation perfectly matches zone C for any of the two configurations, with series maintaining a constant value of the maximum torque, thus being the perfect candidate to operate with.

Deceleration occurs either at breaking or in descending route with energy recovering system working, a situation that matches zone D for both series and parallel configuration, with the series one showing a better performance because of its lower power requirement.

Control system

Because the performance shows different evolution and values throughout the entire range of electric motor turning speed, power and energy demand should be adapted to the optimum operating conditions, this can be done commuting between series and parallel configuration using a control system that configures the operational mode of the DC electric motor to generate optimum performance for every driving situation.

Figure 3 shows the schematic representation of the series configuration for the DC electric motor in propulsion mode; for the regenerative breaking mode, the current is inverted, and the motor plays the role of a generator supplying current and energy to the battery.

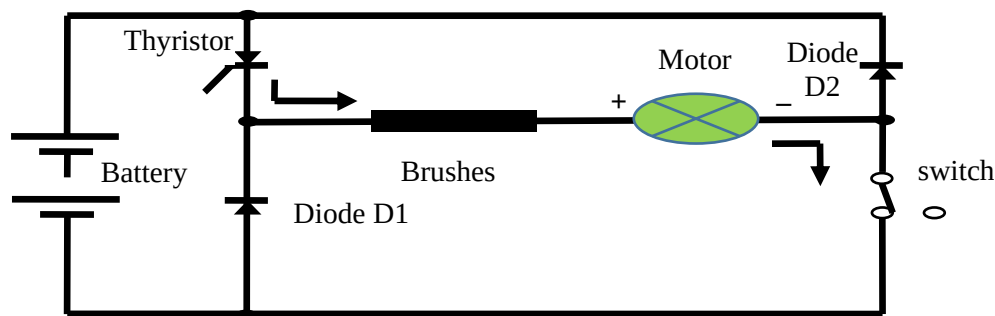


Figure 3. Schematic representation of the electric circuit of the control system for a DC electric motor in series configuration (propulsion mode).

The thyristor is commanded by the control system, regulating the delivering of power according to the specific demand. In the above circuit, the diode D1 forces the current to flow towards the brush system of the motor, causing it to act with direct polarity, thus acting as an energy consuming element (propeller). With the brake switch closed, current flows simultaneously through diode D2 and the brake switch, although the higher resistance of the diode causes most of the current to flow through the brake switch.

Likewise, the current flowing through the lower branch returns, preferentially, to the power source, thus closing the circuit, due to the greater electrical resistance of diode D1. Current flows through diodes D1 and D2, although in less quantity than through the main branch.

In propulsion mode, the thyristor regulates the amount of current that circulates through the upper right branch of the circuit; in this way, the amount of current that is demanded from the DC source is limited by the return current through diode D2, which in turn limits the power of the motor and the energy consumed.

Like a DC motor in series configuration, a DC motor in parallel configuration operates in different regions depending on the speed of the vehicle (Figure 4). The first region of constant torque, limited by the rated power of the motor, corresponds to a fairly small range of speeds. In the second region the motor operates at constant power; in this region the torque varies linearly, decreasing. Finally, in the third region, the torque continues to decrease linearly, while the power decreases, but in a potential way, with the square of the speed.

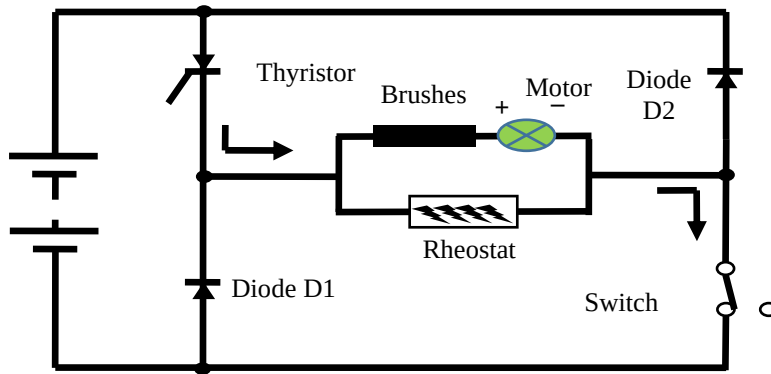


Figure 4. Schematic representation of the electric circuit of the control system for a DC electric motor in parallel configuration (propulsion mode).

In propulsion mode, the current that circulates can be controlled by means of a rheostat, so that the current that circulates through the brushes is greater or less; by varying the circulating current, the field generated in the brushes is also changed, which causes the motor power to change proportionally.

In this type of configuration, starting requires a very high torque that must be regulated by a control system. When you want to increase the speed, you increase the resistance in the rheostat, which causes more current to pass through the brushes, generating more field and, therefore, more power.

If you want to reduce the speed, you have to reduce the power generated by the motor, which is achieved by reducing the field generated in the brushes by passing less current through them, which implies reducing the resistance in the rheostat.

Control system operation

Control system operates based on optimizing the performance of the DC electric motor, which corresponds to the maximum power delivering for specific turning speed. Since the power demand depends on the vehicle velocity, thus on the turning speed of the electric motor, but also on the acceleration rate, it is necessary to configure any driving route as a function of these two reference parameters. According to this definition, five categories arise, acceleration, deceleration, constant speed, ascending and descending route. These five categories should be combined with the different ranges into which the turning speed of the electric motor has been divided (Figure 2) resulting in the following selected configuration (Table 2).

Table 2. Selection of the electric motor configuration for the different driving conditions.

Turning speed range ↓	Acceleration	Deceleration	Cruising	Ascending route	Descending route
Low (A)	Parallel	Series	Series	<i>Parallel</i>	<i>Series</i>
Low-medium (B)	Series	Parallel	Parallel	Series	Parallel
Medium (C)	Series	Parallel	Both	Series	Parallel
High (D)	Parallel	Series	Parallel	Parallel	Series
Very high (E)	Series	Parallel	Parallel	Series	Parallel

NOTE: The selection marked in italic character are very unusual, thus not probable to occur.

The selection criteria for choosing series or parallel configuration at any of the different driving conditions shown in Table 2 have been based on the power and torque requirements, considering a

higher power and torque demand is directly related to a steeper evolution of the power and vice versa. On the other hand, conservative energy and power criteria have been applied to the route segments where power demand lowers or a constant torque works better.

The control system operates on the basis set up by the configuration criteria shown in Table 2, switching from one configuration to the other in case the driving conditions require to do so. Since the turning speed increases or decreases passing through the different turning speed range, once the control system determines the transitional state, it “decides” if switching or maintaining the current configuration.

Let us suppose the electric vehicle is running at low turning speed of the electric motor under acceleration mode; if turning speed increases to low-medium range, and the vehicle continues accelerating the control system switches from parallel to series configuration to adapt the driving conditions to the optimum performance, saving energy and enlarging the driving range. In case the electric vehicle has reached the cruising speed and does not continue accelerating the control system takes no action since the best configuration for cruising at low medium turning speed range is the parallel one. Continuing with the simulation, if from low-medium range of turning speed of electric motor the vehicle enters into ascending route, the control system switches to series as this is the optimum configuration for the new driving conditions. On the way back, if a descending route follows the ascending and the electric vehicle reduces velocity and turning speed the control system switches back to parallel configuration. This simulation is given as a guideline of how the control system works to optimize the performance of the electric motor.

Experimental tests

To validate the set-up protocol an experimental model has been built; the model consists of an DC electric motor that can be configured in parallel or series using an external circuit as shown in Figures 3 and 4. The electric motor is powered by a Li-ion battery of 29.6 Ah operating at 29.4 VDC, which provides a nominal energy of 870.24 Wh. To reproduce the real driving conditions the model has used a conversion factor for voltage, power and current to reduce real operating values to model ones, and the results from the simulation at the model have been converted back into real driving values to verify the validity of the protocol. The electric motor model can turn up to 16000 rpm, so there is no need of conversion factor.

Considering the simulated values of the proposed protocol and taking into consideration the maximum value of the turning speed of the electric motor we can obtain the maximum velocity at which the real electric vehicle can run; therefore:

$$v_{\max} = 2\pi(60)R\omega_{\max}t_r = 2\pi(60)(0.245)(16000)(0.1) = 147.8 \text{ km/h} \quad (17)$$

The maximum velocity obtained from the calculation at the simulation is coherent with technical specifications of a real electric vehicle of the considered characteristics used in the calculation, operating with an electric motor of 60 kW.

The parameter t_r is the transmission rate used in our model to transform rotational speed at the electric motor into rotation movement at the vehicle wheel.

Using this technique, we have obtained the following results (Figure 5).

It can be seen that the model reproduces the real situation within very high accuracy, better than 93%, which proves the validity of the designed protocol.

The analysis of the simulated results provides the threshold values of the different zones, A to E, the turning speed of the electric motor has been divided in. These values are indicated in Table 3.

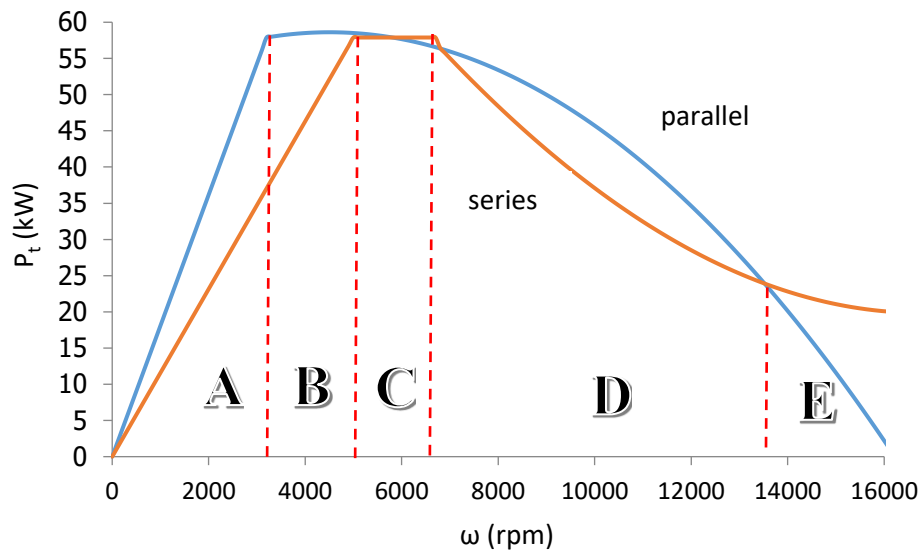


Figure 5. Power evolution for series and parallel configuration of a DC electric motor from experimental test (adapted values to real electric vehicle).

Table 3. Threshold values for the selected zones of the DC electric motor turning speed.

Zone	A-B	B-C	C-D	D-E
Threshold (rpm)	3200	5100	6700	13600

The above-mentioned values in Table 3 are fully compatible with a real electric motor operating in current driving conditions.

CONCLUSIONS

A new protocol to operate with a dual DC electric motor configuration has been studied. Series and parallel configuration have been analyzed when operating at real driving conditions.

The new protocol has been based on power demand requirements to fulfil driving dynamic conditions throughout the entire interval of the turning speed of the electric motor. Five different zones have been identified as a result of the comparison of the DC electric motor performance for series and parallel configuration.

The selection criteria for choosing series or parallel configuration at any of the different driving conditions have been based on power and torque requirements, considering a higher power and torque demand is directly related to a steeper evolution of the power and vice versa. On the other hand, conservative energy and power criteria have been applied to the route segments where power demand lowers or a constant torque works better.

A simulation process of the evolution of electric motor power delivering as a function of the turning speed has been made; the simulation has matched theoretical predictions within accuracy of 93%%.

The simulation process has been validated through experimental tests that have proved the validity of the proposed protocol. As a result of the experimental tests, threshold values to determine the turning speed zone interval have been obtained. These threshold values are compatible with operational real electric motor in electric vehicles.

Maximum velocity of the simulated electric vehicle tests has been obtained; the value is fully compatible with real values, what confirms the validity of the simulation process.

REFERENCES

1. Sjoerd Bakker, Kees Maat, Bert van Wee (2014) Stakeholders interests, expectations, and strategies regarding the development and implementation of electric vehicles: The case of the Netherlands, *Transportation Research Part A: Policy and Practice*, Volume 66, Pages 52-64
 2. Karsten Hedegaard, Hans Ravn, Nina Juul, Peter Meibom (2012) Effects of electric vehicles on power systems in Northern Europe, *Energy*, Volume 48, Issue 1, Pages 356-368
 3. Lina Ingeborgrud, Marianne Ryghaug (2019) The role of practical, cognitive and symbolic factors in the successful implementation of battery electric vehicles in Norway, *Transportation Research Part A: Policy and Practice*, Volume 130, Pages 507-516
 4. Gerardo Zarazua de Rubens (2019) Who will buy electric vehicles after early adopters? Using machine learning to identify the electric vehicle mainstream market, *Energy*, Volume 172, Pages 243-254
 5. Andrés Muñoz-Villamizar, Jairo R. Montoya-Torres, Javier Faulin (2017) Impact of the use of electric vehicles in collaborative urban transport networks: A case study, *Transportation Research Part D: Transport and Environment*, Volume 50, Pages 40-54
 6. Markus Barth, Philipp Jugert, Immo Fritsche (2016) Still under detected – Social norms and collective efficacy predict the acceptance of electric vehicles in Germany, *Transportation Research Part F: Traffic Psychology and Behaviour*, Volume 37, Pages 64-77
 7. Jan Schlüter, Johannes Weyer (2019) Car sharing as a means to raise acceptance of electric vehicles: An empirical study on regime change in automobility, *Transportation Research Part F: Traffic Psychology and Behaviour*, Volume 60, Pages 185-201
 8. Ning Wang, Linhao Tang, Huizhong Pan (2018) Analysis of public acceptance of electric vehicles: An empirical study in Shanghai, *Technological Forecasting and Social Change*, Volume 126, Pages 284-291
 9. Burkert, Amelie, Heiko Fechtner, Benedikt Schmuelling (2021) Interdisciplinary Analysis of Social Acceptance Regarding Electric Vehicles with a Focus on Charging Infrastructure and Driving Range in Germany, *World Electric Vehicle Journal*, Volume 12, no. 1, page 25. <https://doi.org/10.3390/wevj12010025>
 10. Adam Ing (2011). Public Acceptance of Electric Vehicles in Toronto. Proceedings of the 55th Annual Meeting of the ISSS - 2011, Hull, UK, Volume 55, Issue 1. Retrieved from <https://journals.issss.org/index.php/proceedings55th/article/view/1708>
 11. Isabel Neumann, Peter Cocron, Thomas Franke and Josef F. Krems (2010) ELECTRIC VEHICLES AS A SOLUTION FOR GREEN DRIVING IN THE FUTURE? A FIELD STUDY EXAMINING THE USER ACCEPTANCE OF ELECTRIC VEHICLES, *Field Operational Tests and Naturalistic driving Studies / Green ITS*, pages 445-453
 12. Halbey J., Kowalewski S., Ziefle M. (2015) Going on a Road-Trip with My Electric Car: Acceptance Criteria for Long-Distance-Use of Electric Vehicles. In: Marcus A. (eds) *Design, User Experience, and Usability: Interactive Experience Design. DUXU, 2015, Lecture Notes in Computer Science*, volume 9188. Springer, Cham. https://doi.org/10.1007/978-3-319-20889-3_44
 13. Makena Coffman, Paul Bernstein, Sherilyn Wee (2017) Electric vehicles revisited: a review of factors that affect adoption, *Transport Reviews*, Volume 37, Issue 1, pages 79-93, DOI: 10.1080/01441647.2016.1217282
 14. Jingwen Wu, Hua Liao, Jin-Wei Wang, Tianqi Chen (2019) The role of environmental concern in the public acceptance of autonomous electric vehicles: A survey from China, *Transportation Research Part F: Traffic Psychology and Behaviour*, Volume 60, Pages 37-46
 15. Schneider U., Dütschke E., Peters A. (2014) How Does the Actual Usage of Electric Vehicles Influence Consumer Acceptance? In: Hülsmann M., Fornahl D. (eds) *Evolutionary Paths Towards the Mobility Patterns of the Future. Lecture Notes in Mobility*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-37558-3_4
 16. Wenbo Li, Ruyin Long, Hong Chen, Jichao Geng (2017) A review of factors influencing consumer intentions to adopt battery electric vehicles, *Renewable and Sustainable Energy Reviews*, Volume 78, Pages 318-328
-

17. Park, Eunil, Jooyoung Lim, Yongwoo Cho (2018) Understanding the Emergence and Social Acceptance of Electric Vehicles as Next-Generation Models for the Automobile Industry, Sustainability, Volume 10, no. 3, page 662. <https://doi.org/10.3390/su10030662>
18. Fanchao Liao, Eric Molin, Bert van Wee (2017) Consumer preferences for electric vehicles: a literature review, Transport Reviews, Volume 37, Issue 3, pages 252-275, DOI: 10.1080/01441647.2016.1230794
19. VRÖSCH, Bob Johan Alexander - Consumer' acceptance of electric vehicles in Lisbon, Lisboa: ISCTE-IUL, 2018. Dissertação de mestrado. Disponível em [www:http://hdl.handle.net/10071/18980](http://hdl.handle.net/10071/18980).
20. C. Armenta-Déu, J.P. Carriquiry (2020) Application of Statistical Method To Determine Battery Capacity for Electric Vehicles, Journal of Automobile Engineering and Applications, Volume 7, Issue 2, pages 40-49
21. M. Hanako Olmediall-Ishishi, C. Armenta-Déu (2020) Seasonal Variation of Electric Vehicles Autonomy: Application to AC/DC Dual Voltage Operation, Journal of Mechatronics and Automation, Volume 7, Issue 3, pages 1-16
22. C. Armenta-Déu, E. Cattin (2021) Real Driving Range in Electric Vehicles: Influence of Fuel Consumption and Carbon Emissions, World Electric Vehicle Journal, Volume 12, Issue 4, page 166
23. L. García-Arranz, C. Armenta-Déu (2021) Performance Tests To Determine Driving Range in Electric Vehicles, Journal of Mechatronics and Automation, Volume 8, Issue 2, pages 10-20
24. C. Armenta-Déu, J.P. Carriquiry (2021) Scale Simulation of Battery Performance for Electric Vehicles, International Journal of Vehicle Systems Modelling and Testing, Volume 15, Nos 2/3, pages 164-187
25. Ricardo Maia, Marco Silva, Rui Araújo, Urbano Nunes (2011) Electric vehicle simulator for energy consumption studies in electric mobility systems, IEEE Forum on Integrated and Sustainable Transportation Systems, 29 June-1 July 2011, IEEE Xplore, INSPEC Accession Number: 12170757, DOI: 10.1109/FISTS.2011.5973655
26. Ali Emadi, Young Joo Lee, Kaushik Rajashekara (2008) Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles, IEEE Transactions on Industrial Electronics (Volume: 55, Issue: 6, June 2008)
27. Sida Feng, Christopher L.Magee (2020) Technological development of key domains in electric vehicles: Improvement rates, technology trajectories and key assignees, Applied Energy, Volume 260, 114264
28. Agamloh, Emmanuel, Annette von Jouanne, Alexandre Yokochi (2020) An Overview of Electric Machine Trends in Modern Electric Vehicles, Machines, Volume 8, no. 2, page 20. <https://doi.org/10.3390/machines8020020>
29. E.P. Cornell, R.H. Guess, F.G. Turnbull (1977) Advanced motor developments for electric vehicles, IEEE Transactions on Vehicular Technology, Volume 26, Issue 2, Pages 128 – 134
30. New advances in electric motors, World Highways, <https://www.worldhighways.com/news/new-advances-electric-motors> [Accessed on 29/12/2021]
31. Tian-Hua Liu, Woei-Luen Chen (2021) Latest Advances on Electric Motor Drives, Controls, Reliability Improvement and Battery Management, <https://www.frontiersin.org/research-topics/16069/latest-advances-on-electric-motor-drives-controls-reliability-improvement-and-battery-management> [Accessed on 29/12/2021]
32. Advances in Energy-Efficient AC Motor Design: Soft Magnetic Composite, Horizon Technologies, 2021, <https://www.horizontechnology.biz/blog/advances-in-energy-efficient-ac-motor-design-electric>
33. JAMES BILLINGTON (2021) New electric motor design revealed that could 'revolutionize' EV performance and manufacturing, Motor Technology, electric & hybrid vehicle technology international, <https://www.electrichybridvehicletechnology.com/news/motor-technology/new-electric-motor-design-revealed-that-could-revolutionize-ev-performance-and-manufacturing.html> [Accessed on 29/12/2021]

34. Bhatt, Pooja and Mehar, Hemant and Sahajwani, Manish, Electrical Motors for Electric Vehicle – A Comparative Study (April 3, 2019). Proceedings of Recent Advances in Interdisciplinary Trends in Engineering & Applications (RAITEA) 2019, Available at SSRN: <https://ssrn.com/abstract=3364887> or <http://dx.doi.org/10.2139/ssrn.3364887>
35. Jason Torchinsky (2019) A Texas Startup Claims To Have Made The Biggest Advancements In Electric Motor Designs In Over A Century, Jalopnik, <https://jalopnik.com/a-texas-startup-claims-to-have-made-the-biggest-advance-1837173127> [Accessed on 29/12/2021]
36. M. Martínez-Arriaga, C. Armenta-Déu (2020) Simulation of the Performance of Electric Vehicle Batteries Under Variable Driving Conditions, Journal of Automobile Engineering and Applications, Volume 7, Issue 3, pages 1-15
37. Jiménez Felipe, Juan Carlos Amarillo, Jose Eugenio Naranjo, Francisco Serradilla, Alberto Díaz (2015) Energy Consumption Estimation in Electric Vehicles Considering Driving Style, IEEE 18th International Conference on Intelligent Transportation Systems, 15-18 Sept. 2015, IEEE Xplore, INSPEC Accession Number: 15572805, DOI: 10.1109/ITSC.2015.25
38. N. Hashemnia, B. Asaei, "Comparative study of using different electric motors in the electric vehicles," 2008 18th International Conference on Electrical Machines, 2008, pp. 1-5, doi: 10.1109/ICELMACH.2008.4800157
39. L. Chang, "Comparison of AC drives for electric vehicles-a report on experts' opinion survey," in IEEE Aerospace and Electronic Systems Magazine, vol. 9, no. 8, pp. 7-11, Aug. 1994, doi: 10.1109/62.311235.
40. Singh, K.V., Bansal, H.O. & Singh, D. A comprehensive review on hybrid electric vehicles: architectures and components. J. Mod. Transport. 27, 77–107 (2019). <https://doi.org/10.1007/s40534-019-0184-3>
41. J. de Santiago et al., "Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review," in IEEE Transactions on Vehicular Technology, vol. 61, no. 2, pp. 475-484, Feb. 2012, doi: 10.1109/TVT.2011.2177873.
42. E. Roshandel, A. Mahmoudi, S. Kahourzade, A. Tahir and N. Fernando, "Propulsion System of Electric Vehicles: Review," 2021 31st Australasian Universities Power Engineering Conference (AUPEC), 2021, pp. 1-6, doi: 10.1109/AUPEC52110.2021.9597828.
43. Learning Science and Technology. Calculation of vehicle speed from engine turning speed. <https://aprendecienciaytecnologia.com/2018/09/19/como-se-calcula-la-velocidad-de-un-vehiculo-a-partir-de-las-revoluciones-del-motor/> [Accessed online: 28/01/2022]
44. https://www.mobilityhouse.com/int_en/knowledge-center/charging-time-summary [Accessed online: 20/02/2022]