Optimized Analytical Crone Controller for Electric Vehicle System

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Abstract. The usage of Fractional Order (FO) controllers for an electrical vehicle system is examined in this research (EVS). The auxiliary batteries, controller, charging port, onboard charger, electric motor, power in veelectriction battery pack, DC-DC converter, transmission, and thermal cooling system are only a few of the components used by the Electrical Vehicle System (EVS). A FO control method is used to achieve system performance requirements, and the Fractional Order-PID controller parameters are adjusted by means of a Nelder-Mead optimization procedure. Numerical simulations demonstrate the viability of the suggested methods. The findings of the crone controller are compared with those of the fractional order (FO) and integer order (IO) controllers, and the relative strengths and shortcomings of the modeling are evaluated. This particular FOC has proved to be superior to traditional methods. Moreover, the analysis of the system cross-checked with crone controller.

Keywords: Robust Controller · Sensitivity · Complementary sensitivity function · electrical vehicle performance indices

1 Introduction

Due to the extensive resources for its applications, the fractional order calculus industry is expanding [1]. In recent years, many systems have started to fractional order calculus to get superior results than any integer order calculus. For any differential solution, an integer order solution exists but a fractional order solution does not [2, 3]. Therefore, to know the effect of a fractional order controller on a transfer function one must first convert an integer order transfer function to a fractional order transfer function and then fairly accurate this fractional-order transfer function to an integer order transfer function using Oustapp or any other related methods.

At present, there is the cumbersome task of realizing a Fractional order controller as a model [4, 5]. But simulation of the same can be done to get better results. Currently, the industry is a booming one where researchers are trying hard to acquire desired results. So it would not be long to be able to make a model of the same. The investigation of

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observability, as of today controllability & stability of irrational order systems are the latest trending topics dealt with by researchers.

Managing industrial facilities necessitates meeting a variety of requirements. Hence, a variety of strategies are required. Integer order controllers are utilised for controlling in a lot of industrial applications. Modern industrial applications use fractional order (FOPID) controllers to enhance system control performance [4–7]. The controller is the most prevalent type of fractional order PID controller. FOPID controllers offer additional flexibility for designing integral and derivative commands as well as controller gains [8, 9]. Instead of having to be integers, the derivative and integral orders can be real numbers. The FOPID controller expands the traditional integer order PID controller from a point to a plane, as depicted in Fig. 1. This growth could bring about a lot.

2 Methodology

Fractional-order calculus is defined as:

$$aD_t^{\alpha} = \begin{cases} \frac{d^a}{dt^{\alpha}}, Re\ \alpha > 0 \\ 1, Re\,\alpha = 0 \\ \int_a^t (d\tau)^{-\alpha}, Re\ \alpha < 0 \end{cases} \tag{1}$$

Where 't' & 'a' are the operation's bounds and 'α' denotes the order of fractional calculus. Here, α can be a real or a complex value [4]. The generalized fractional-order differential equations (FODEs) are given as

$$\begin{aligned} a_n D^{\alpha_n} y(t) + a_{n-1} D^{\alpha_n - 1} D^{\alpha_n - 1} y(t) + \ldots\ldots a_0 D^{\alpha_0} y(t) = b_n D^{\beta_n} u(t) \\ + b_{n-1} D^{\beta_n - 1} u(t) + \ldots\ldots b_0 D^{\alpha_0} u(t) \end{aligned} \tag{2}$$

Where, $(a_i, b_j) \in R^2$ and $(\alpha_i, \beta_j) \in R^2$. The transfer function with fractional orders that it represents the processing model having an input delay term is

$$G(S) = \frac{b_n S^{\beta_n} + b_{n-1} S^{\beta_n - 1} + \ldots\ldots b_0 S^{\alpha_0}}{a_n S^{\alpha_n} + a_{n-1} S^{\alpha_n - 1} + \ldots\ldots a_0 D^{\alpha_0}} e^{-Ls} (3) \tag{3}$$

where, $(a_i, b_j) \in R^2$ and $(\alpha_i, \beta_j) \in R^2$. The transfer function with fractional orders that it represents the processing model having an input delay term is

3 Generalized Fraction Order Control

The theorized form of a rational-order PID controller is in the form

$$G(S) = K_P + K_i S^{-\lambda} + K_d S^{\mu} \tag{4}$$

Where, λ and μ are orders of integration and differentiation, respectively and the operators of integral and derivative are rationalized in nature. The systematic way of changing the values of λ and μ according to the necessity i.e. PI ($\lambda = 1$ and $\mu = 0$), PD ($\lambda = 0$ and $\mu = 1$), PID ($\lambda = 1$ and $\mu = 1$), the various forms of PID controllers can be obtained to meet requirements.

3.1 Feedback Control System

Its main objective is to design a control system with a set of standards in mind. So that the output can be set to a constant value, often known as a reference value, the reference value should remain constant not withstanding any unidentified disruptions. The first is known as tracking, the second is disturbance rejection, and if the condition is satisfied, the control system design can be a reliable servomechanism. Reduce errors automatically. Greater stability increasing resistance to outside disturbances.

3.2 Time Domain Analysis

Finding the ideal set of settings for the FOPID and PID controller involves iteratively minimising various integral performance indices starting from randomly initialised values. If the objective function's value does not significantly change over a number of iterations, the algorithm stops.

While constructing time-domain controllers, controllers strive to minimise a variety of integral performance metrics, specifically:

$$\text{Integral square Error (ISE)} = \int_0^{\tau} \boldsymbol{e}^2(\boldsymbol{t})\boldsymbol{dt} \tag{5}$$

$$\text{Integral absolute Error (IAE)} = \int_0^{\tau} |\boldsymbol{e}(\boldsymbol{t})|\boldsymbol{dt} \tag{6}$$

$$\text{Integral time - square Error (ITSE)} = \int_0^{\tau} \mathrm{te}^2(\boldsymbol{t})\boldsymbol{dt} \tag{7}$$

$$\text{Integral time - absolute Error (ITAE)} = \int_0^{\tau} \boldsymbol{t}|\boldsymbol{e}(\boldsymbol{t})|\boldsymbol{dt} \tag{8}$$

A highly potent robustness indication is the necessity for a PID controller with fractional order, which includes the phase margin and the gain crossover frequency. Equation (9) provide the gain crossover frequency and the phase margin

$$\left|C\left(j\omega_{cg}\right)G\left(j\omega_{cg}\right)\right| = 0dB\&arg\left(C\left(j\omega_{cg}\right)G\left(j\omega_{cg}\right)\right) = \pi + \phi_m \tag{9}$$

Adaptability of the plant's gain to change:

The open loop system's phase is forced to be flat at the crossover frequency as a result of this limitation, and it stays nearly constant in this region around the crossover frequency.

$$\left(\frac{dargC(j\omega)G(j\omega)}{dC(\omega)}\right)\left(\frac{dargC(j\omega)G(j\omega)}{dC(\omega)}\right)_{\omega=\omega_{cg}} = 0 \tag{10}$$

High-frequency noise rejection:

The following condition can be used to represent this supplementary sensitivity function limitation.

$$\left\|T(j\omega) = \frac{C(j\omega)G(j\omega)}{1 + C(j\omega)G(j\omega)}\right\|_{dB} \leq AdB \tag{11}$$

where A dB represents the desired reduction in noise in the lower frequency band i.e. ω_s rad/sec.

3.3 Output Disturbance Denial

This is a constraint on the sensitivity function that may be written as

$$\left| S(j\omega) = \frac{1}{1 + C(j\omega)G(j\omega)} \right| \leq BdB \tag{12}$$

where B dB represents the value of the sensitivity function in the frequency band as below ω_S rad/sec.

Eliminating the steady state error:

The closed loop system's steady state inaccuracy can be eliminated by adding a fractional order integrator. Different kind of design parameters can also be met according to the demand of the system. The fractional order controller is constructed using the aforementioned limitation as well as several other constraints depending on the required requirements for the system. The irrational order controller will meet more of the design requirements of a control system than the integer order controller.

4 Description of EV

Electrical vehicle is a machine, which takes voltage as input and gives mechanical speed as output, the basic energy flow starts from the battery pack to power electronic devices and then an electric traction motor will be powered by them, the rotor of the motor is mechanically coupled to the shaft of the wheels, which in turns develops the motion of the vehicle, through the on-board charger, the battery pack will gets charged and powers the vehicle.

The force-balance equation makes use of Newton's laws of motion by a technique called mathematical modelling and the governed equation is as follows (Table 1).

$$F = fmg\cos\alpha + mg\sin\alpha + 0.5\rho C_w A(v + v_{hw})^2 + k_m ma \tag{13}$$

By using F-V or F-I analogy convert the mechanical in to electrical parameters and obtain the integer order transfer function (IOTF) of the system by substituting the above typical values in it and it as follows

$$\text{IOTF} = \frac{0.913242}{1.39S^2 + 1.215S + 0.913242} \tag{14}$$

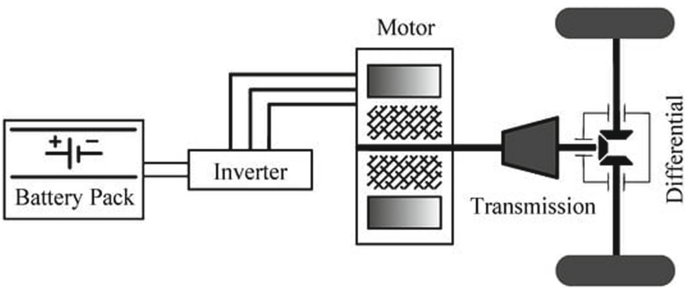


Fig. 1. Block diagram of electrical vehicle

Table 1. Parameters description and typical values

Parameter	Description	Typical Values
m	mass of the car in kg	1590 kg
f	Coefficient of rolling resistance	0.011
C_W	Coefficient of aerodynamic drag,	0.3
k_m	Coefficient to compensate for apparent increase in vehicle mass to rotating masses	1.2
P	air density, in kg/m^3	1.2 kg/m^3
A	largest cross-section of the car, in m^2	2.0 m^2
G	gravitational acceleration, in m/s^2	9.8 m/s^2
A	Inclination of path on which car rides	
V	Velocity of the car	

Table. 2 Results obtained for PID parameter of the system under consideration

k_p	k_i	k_d
0.6885	0.5454	0.2173

5 PID Tuning

The parameters obtained for the PID regulator namely k_p, k_i, k_d by Ziegler Nicholas method or Ant colony optimization technique, but in simulation there is a tool called PID tuner which directly gives the parameters when the plant transfer function entered as an input and obtained parameters are as follows (Table 2).

As per the system concern, two gains are available. One from plant and another from controller so by cascading them open loop transfer function build up, then calculate closed loop transfer function of system by using appropriate MATLAB instructions. Obtained results of time domain specifications are as follows (Table 3).

6 Optimization Technique

Generally, any optimization technique is used to obtain the design parameters as per the requirements. Here the use of four different kinds of optimization techniques, the parameters are optimized in simulation process with an extension called FOMCON, which is exceptionally used for simulating fractional order systems, this extension is facilitated with inbuilt optimization algorithms.

a. ***NELDER-MEAD method***

In 1965, Nelder-Mead created the simplest method for identifying a local minimum of a function with numerous variables. Triangles represent simplexes for two variables, and

Table 3. Results obtained for time domain specifications of system under consideration

Time domain specification	Value
Rise time	2.4209s
Settling time	9.3037s
overshoot	3.2826%
undershoot	0
peak	1.0382
Peak time	4.2995s

the method is a pattern search that contrasts the function values at each of the triangle's three vertices. Baddest vertex, whose functional value is greatest, is disregarded and a new vertex is added in its place. The search is resumed while a fresh triangle is formed. The procedure creates a series of triangles with decreasing functional values at the vertices. Triangle sizes are shrunk, and the coordinates of the smallest point are discovered (Table 4).

b. ***INTERIOR-POINT method***

A particular class of algorithms for solving linear and non-linear convex optimization problems includes interior point methods and barrier methods. By adding a barrier component to the goal function that makes the ideal unconstrained value reside in the feasible space, inequality restrictions are prevented from being violated (Table 5).

c. ***Sequential quadratic programming (SQP) method***

Constrained nonlinear optimization is accomplished through the iterative process of sequential quadratic programming. A series of optimization subproblems are solved by SQP techniques, and each one optimises a quadratic model of the goal while taking the constraints' linearization into account. The procedure reduces to Newton's approach for locating a place where the gradient of the objective vanishes if the problem is unconstrained. The approach is comparable to applying Newton's method to the problem's

Table 4. Results are obtained for the system with FOPID controller by using N-M optimization technique.

Time domain specifications	ISE	IAE	ITSE	ITAE
Rise time	0.8774s	0.7546s	0.5938s	0.9769s
Peak time	0.9914s	1.3742s	1.4263s	1.7175s
Over shoot	1.0002	1.8735	32.5291	1.2216
Peak	0.9914	1.0002	1.3179	0.9925
Settling time	101.01s	99.378s	14.361s	108.02s

Table 5. Results are obtained for the system with FOPID controller by using the interior point optimization technique.

Time domain specifications	ISE	IAE	ITSE	ITAE
Rise time	0.3214s	1.6873s	0.6821s	0.0515s
Peak time	0.6718s	4.2706s	2.0849s	0.1152s
Over shoot	7.8731	14.5707	9.8074	7.2554
Peak	1.0766	1.1451	1.0977	1.0717
Settling time	7.4643s	14.0932s	7.0749s	0.2077s

first order optimality criteria, also known as the Karush-Kuhn-Tucker conditions, if the only constraints on the solution are equality constraints (Table 6).

d. ***ACTIVE SET method:***

In optimization theory, the active set plays a crucial role in identifying the constraints that will have an impact on the optimization's outcome. For instance, the active set provides the hyperplane that intersects at the solution point while solving the linear programming issue. In quadratic programming, the subset of inequalities can be observed while finding the answer to a function by estimating the active set of a function. And because of observation o inequalities, which lowers the complexity of the search process, because the answer is not always on one of the edges of the enclosing polygon (Table 7).

From Table 8, none of the specified optimization techniques produces the entire time domain specifications. Only few parameters are improved in every method. So best of the available methods is the NELDER-MEAD method only because in this method maximum of two parameters are improved.

From Table 9 none of the specified optimization techniques produces the entire time domain specifications. Only a few parameters are improved in every method. So the best of the available methods is the NELDER-MEAD method only because, in this method maximum three parameters are improved. Rise time, peak over shoot and peak time superior in this method compared to all other methods.

From Table 10, it is observed that, none of the specified optimization techniques improves all the time domain specifications. Only few parameters are improved in every

Table 6. Results are obtained for the system with FOPID controller by using SQP method.

Time domain specifications	ISE	IAE	ITSE	ITAE
Rise time	0.6139s	0.7928s	0.5216s	0.8923s
Peak time	1.297s	1.8706s	1.0283s	1.070s
Over shoot	5.868	22.614	5.809	7.145
Peak	1.051	1.225	1.057	1.070
Settling time	18.719s	5.9917s	4.3118s	2.498s

Table 7. Results obtained for the system with FOPID controller by using active set optimization technique.

Time domain specifications	ISE	IAE	ITSE	ITAE
Rise time	0.13s	0.832s	1.628s	0.095s
Peak time	0.288s	1.608s	11.018s	0.2168s
Over shoot	9.003	4.577	10.152	9.3201
Peak	1.087	1.045	1.0993	1.093
Settling time	0.5334s	0.9196s	22.7821s	NaN

Table 8. ISE with various OT and time domain specifications

ISE	Rise time	Over shoot	Peak	Settling time
N-M	0.8774s	1.0002	0.9914	101.01s
I-P	0.3214s	7.8731	1.0766	7.4643s
SQP	0.6139s	5.868	1.051	18.719s
Active	0.13s	9.003	1.087	0.5334s

Table 9. IAE with various OT and time domain specifications

IAE	Rise time	Over shoot	Peak	Settling time
N-M	0.7546s	1.8735	1.0002	99.378s
I-P	1.6873s	14.5707	1.1451	14.0932s
SQP	0.7928s	22.614	1.225	5.9917s
Active	0.832s	4.577	1.045	0.9196s

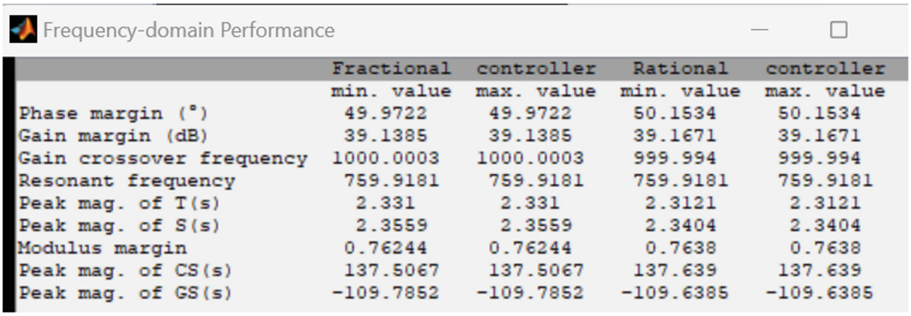
Table 10. ISTE with various OT and time domain specifications

ISTE	Rise time	Over shoot	Peak	Settling time
N-M	0.5938s	32.5291	1.3179	14.361s
I-P	0.6821s	9.8074	1.0977	7.0749s
SQP	0.5216s	5.809	1.057	4.3118s
Active	0.5216s	10.152	1.0993	22.7821s

method. So best of the available methods is SQP method only because, in this method maximum three parameters are improved. Rise time, crest over shoot and crest time superior in this method compared to all other methods.

Table 11. ITAE with various OT and time domain specifications

ITAE	Rise time	Over shoot	Peak	Settling time
N-M	0.9769s	1.2216	0.9925	108.02s
I-P	0.0515s	7.2554	1.0717	0.2077s
SQP	0.8923s	7.145	1.07	2.498s
Active	0.095s	9.3201	1.093	NaN


Frequency-domain Performance

	Fractional controller min. value	Fractional controller max. value	Rational controller min. value	Rational controller max. value
Phase margin (°)	49.9722	49.9722	50.1534	50.1534
Gain margin (dB)	39.1385	39.1385	39.1671	39.1671
Gain crossover frequency	1000.0003	1000.0003	999.994	999.994
Resonant frequency	759.9181	759.9181	759.9181	759.9181
Peak mag. of T(s)	2.331	2.331	2.3121	2.3121
Peak mag. of S(s)	2.3559	2.3559	2.3404	2.3404
Modulus margin	0.76244	0.76244	0.7638	0.7638
Peak mag. of CS(s)	137.5067	137.5067	137.639	137.639
Peak mag. of GS(s)	-109.7852	-109.7852	-109.6385	-109.6385

Fig. 2. Stability margins with Irrational (Crone) and Rational order controller.

From Table 11 none of the specified optimization techniques produces the entire time domain specifications. Only few parameters are improved in every method. So best of the available methods is NELDER-MEAD method only because, in this method maximum three parameters are improved. Rise time, peak over shoot and peak time superior in this method compared to all other methods.

Controllers aim at minimization of different integral performance indices. From the above discussion, the NELDER-MEAD method is superior, because in this method most of the error parameters are improved (Figs. 2, 3, 4, and 5).

7 Observations

8 Result and Discussion

From the above observations, when a system is controlled with PID controller it will have good performance, instead of it FOPID controller will give better results than PID controller and also performance indices like ISE, IAE, IATE, IASE errors got reduced then output accuracy is increased. Besides these, time domain specifications improved in value, main parameter over shoot decreased then frequency of oscillations reduced, so overall performance of a system got improved.

The better results are possible with FOPID, because of the two extra parameters. With extra parameters, fractional powers are possible is comparison to traditional PID controller. For example, in traditional PID, order of the system can be only integer but in

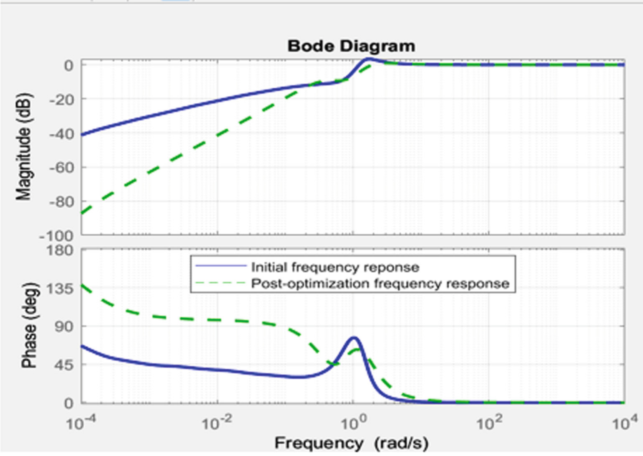


Fig. 3. Sensitivity function comparison of Irrational and Rational order controller on plant

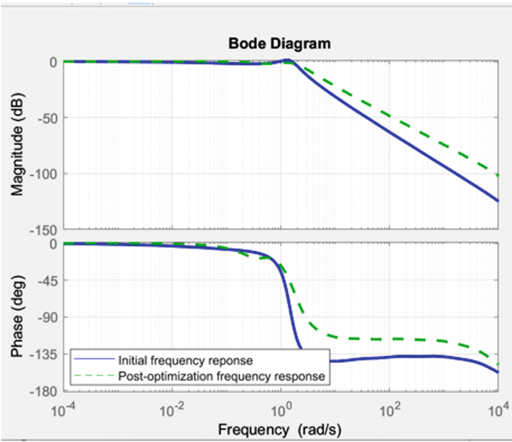


Fig. 4. Complementary Sensitivity function comparison of Irrational and Rational order controller on plant

FOPID multiple orders are possible in between any two consecutive integers, so scope of variation trial and error is large, in this process accurate results are possible.

9 Conclusion

In this paper, the comparison of the PID, FOPID controller mechanisms and their performances and also comparison between different kinds of optimization techniques to generate better output. From Table 9, with Nelder-Mead rise time is less as minimum as 21% and maximum 124%, peak overshoot also less than other methods as minimum 4.6% and maximum 42%. And peak time is less as minimum as 4% and maximum by 22% respectively. These statistics shows that FOPID is superior to traditional PID.

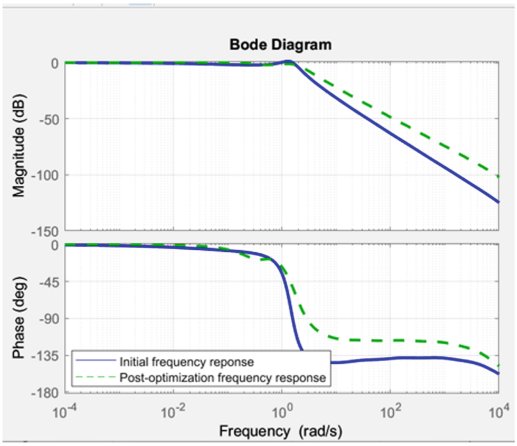


Fig. 5. Controller effect on plant system

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