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# Fractional Order Control of Power Electronic Converters in Industrial Drives and Renewable Energy Systems: A Review

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**ABSTRACT** The power electronics industry is undergoing a revolution driven by an industry 4.0 perspective, with smart and green/hybrid energy management systems being the requirement of the future. There is a need to highlight the potential of fractional order control in power electronics for the highly efficient systems of tomorrow. This paper reviews the developments in fractional order control in power electronics ranging from stand-alone power converters, industrial drives and electric vehicles to renewable energy systems and management in smart grids and microgrids. Various controllers used in power electronics such as the fractional order PI/PID (FOPI/FOPID) and fractional-order sliding mode controllers have been discussed in detail. This review indicates that the plug-and-play type of intelligent fractional order systems needs to be developed for our sustainable future. The review also points out that there is tremendous scope for the design of modular fractional-order intelligent controllers. Such controllers can be embedded into power converters, resulting in smart power electronic systems that contribute to the faster and greener implementation of industry 4.0 standards.

**INDEX TERMS** Fractional calculus, power electronic converters, fractional order control, industrial drives, electric vehicles, renewable energy applications, smart grids and microgrids, industry 4.0.

## I. INTRODUCTION

The $21^{st}$ century power electronic systems should cater to the Industry 4.0 standard which envisages an energy sector which will eventually become more distributed, with smart devices and systems connected by IOT [1]. The need for cleaner and greener energy is being accelerated by the rapid development of energy management technology in smart grids, integrating smart devices, sensors, storage devices, renewable energy systems etc. using communication networks [2], [3] (Fig 1). Indeed, a new keyword such as Cognitive Power Electronics 4.0 was coined by Fraunhofer IISB, which develops innovative and modular power electronic systems wherein smart and robust controllers can be integrated with power converters [4].

Power electronics involves the conversion, control and conditioning of power using power semiconductor devices to suit the load requirements [5]. Modern power converters may involve multiple stages of power conversion. Applications of power electronics cover a wide spectrum including consumer electronics, switched-mode power supplies (SMPS), Uninterrupted Power Supplies (UPS), heating and lighting control, smart actuator based systems such as switched-mode variable speed motor drives, High Voltage DC Systems (HVDC), fuel cell technology, photovoltaic systems, wind energy systems, electric and hybrid vehicles, aircraft systems, grid-connected inverters etc., [6].

Power converters are inherently nonlinear due to the switching devices, voltage clamping, load variations, magnetic components that may saturate, etc., [7]–[9]. Efficient control of the power converters is therefore crucial to the performance of power electronic systems. The main control objectives are to design cost-effective, reliable and robust systems with high energy efficiency, packaging density and less complexity. The choice of the controller should be based on measures such as the robustness, accuracy, and stability, and also the dynamic performance of the controller such as fast response, disturbance rejection, etc., [9]. The commonly used control strategies for power converters are PI or PID control, sliding mode control, dead beat control, $H_\infty$, optimal control, predictive control etc., [9]–[11]. Recently, intelligent

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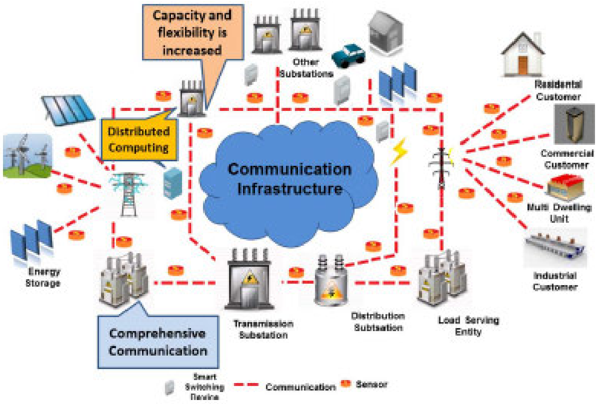


FIGURE 1. **Smart grid concept [3].**

controllers employing fuzzy and artificial neural networks have become popular for power electronic control due to their capacity for representation of non-linearities [12], [13].

### A. RELEVANCE OF FRACTIONAL ORDER CONTROL

Fractional calculus has been extensively used in the field of control systems, wherein fractional order differentiation and integration can be used in the controller [14]. It generalizes conventional integer order calculus by using real, complex, variable or distributed order operators [15], [16]. Fractional controllers have gained popularity in recent years because of their robustness towards plant gain variations and plant uncertainties. Design specifications such as gain and phase margins can be adjusted with more flexibility using fractional order (FO) controllers in comparison to integer-order (IO) controllers. Using fewer tuning knobs, the FO controller gives more robustness which could be attained only with very high order IO controllers [17]. The fractional operators or differintegrals, as they are called, have memory, i.e., they can store the former states and hence improve the filtering action. This property helps in reducing the control effort. Thus a smoother control signal is obtained with a FO controller compared to an IO controller [18]. The FO controllers have more parameters than IO controllers, due to which more design specifications can be satisfied. Thus more robust and precise control systems can be designed using fractional control.

The past decade has seen remarkable growth in the control and modeling of power electronic systems using fractional calculus. Proportional Integral(PI) and Proportional Integral Derivative (PID) controllers are the most commonly used controllers in the industry. Recently, a considerable amount of research has been done on fractional-order PI/PID controllers for various DC-DC converters, electrical drives, grid-connected and/or photovoltaic inverters, fractional controllers for multi-level converters in wind energy applications, microgrids, maximum power point tracking (MPPT) control of photovoltaic panels and in electric and hybrid vehicles [19]–[22]. More robust systems can be designed using fractional control with a remarkable improvement in the dynamic response compared to the conventional integer-order control. Combinations of fuzzy logic systems with fractional control have also been implemented and were shown to combine the advantages of both forms of control. Simulation and hardware implementations show that fractional control can be effectively used in power electronic systems to give better results than conventional controllers [23]. This paper reviews the use of fractional order controllers in some of the main applications of power electronics, with special emphasis on the potential of FO control in the renewable energy sector.

### B. PAPER LAYOUT

The paper layout is described below.

1) Section 2 gives the definitions of fractional calculus, and various software tools associated with fractional order modeling and control. Also, common fractional order controllers and their analog implementations have been discussed.
2) In section 3, the various fractional controllers used for power converters are discussed.
3) Section 4 discusses fractional order control in industrial drives.
4) Section 5 reviews the applications of fractional controller in renewable energy applications such as solar and wind energy systems. Moreover, application of fractional order to energy management systems in smart grids, microgrids and in electric vehicles is discussed.
5) Section 6 discusses the advantages and limitations of various fractional order controllers.
6) The seventh section is a discussion on how to overcome the limitations of FO controllers and utilize their full potential.
7) In the last section, the conclusions and future trends in fractional order controller for power electronics are presented.

## II. BASICS OF FRACTIONAL ORDER SYSTEMS

Conventional calculus deals with derivatives and integrals having integer order (d/dx, $d^2/dx^2$ etc.). The discussion between L' Hopital and Leibniz about the possibility of non-integer order in calculus in the seventeenth century led to the birth of fractional calculus [24]. Since then, many great mathematicians contributed to the development of fractional calculus [15], [24].

Fractional calculus defines the continuous integro-differential operator ${}_cD_t^\alpha$, where $\alpha$ is the order of operation and could be real or complex, $c$ and $t$ are the limits of the operation, and R($\alpha$) is the real part of $\alpha$. This operator combines both differentiation and integration [17].

$$ {}_cD_t^\alpha = \begin{cases} \dfrac{d^\alpha}{dt^\alpha}; & R(\alpha) > 0 \\ 1; & \alpha = 0 \\ \displaystyle\int_c^t (d\tau)^{-\alpha}; & R(\alpha) < 0 \end{cases} \tag{1} $$

### A. DEFINITIONS

There are many definitions of fractional calculus, the most famous are the Grunwald-Letnikov, Riemann-Liouville (RL) and Caputo definitions [25].

#### 1) GRUNWALD-LETNIKOV DEFINITION

$$ {}_cD_t^\alpha\ (f(t)) = \lim_{h\to 0}\frac{1}{h^\alpha}\sum_{r=0}^{[(\frac{t-c}{h})]}(-1)^r\binom{\alpha}{r}f(t-rh) \qquad (2)$$

Here, [.] implies the integer part, and the combination is defined as:

$$\binom{\alpha}{r} = \frac{\Gamma(\alpha+1)}{\Gamma(r+1)\Gamma(\alpha-r+1)} \qquad (3)$$

The Gamma ($\Gamma$) function is crucial in fractional calculus and is defined as:

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt;\, R(x) > 0 \qquad (4)$$

#### 2) RIEMANN-LIOUVILLE DEFINITION

$$ {}_cD_t^\alpha\ (f(t)) = D^nJ^{n-\alpha}(f(t)) \qquad (5)$$

$$ {}_cD_t^\alpha\ (f(t)) = \frac{1}{\Gamma(n-\alpha)}\left(\frac{d}{dt}\right)^n\int_c^t\frac{f(\tau)}{(t-\tau)^{\alpha-n+1}}d\tau \qquad (6)$$

Here, $J$ is defined as the fractional integral operator, $n$ is an integer and $\alpha$ is a real number such that $n-1 < \alpha < n$. Often, the operator $D^{-n}$ is also seen to be used for the operator $J^n$ [26].

#### 3) CAPUTO's DEFINITION

In both Riemann-Liouville and Caputo definitions, $n$ is an integer such that $n-1 < \alpha < n, \alpha$ is the fractional order such as 0.5, and $\{c, t\}$ are the limits of integration. The Caputo definition provides a more practical and real-world interpretation, as it involves integer order initial conditions, which are physically realizable. The fractional derivative of a constant is zero in Caputo definition, but this is not the case for RL definition [26]. It is defined by

$$ {}_cD_t^\alpha\ (f(t)) = \frac{1}{\Gamma(n-\alpha)}\int_c^t\frac{f^n(\tau)}{(t-\tau)^{\alpha-n+1}}d\tau \qquad (7)$$

The fractional-order systems can be considered to be infinite-dimensional filters since the transfer function has irrational terms, due to which they have unlimited memory. Integer-order systems are a special case of the non-integer order, with limited memory. Hence, the practical realizations of fractional order systems require some integer-order approximations. There are analog approximation methods and digital approximation methods, the latter being preferred for direct implementation with digital signal processors. Some of the well-known approximation techniques are Carlson's approximation, Matsuda's method, Oustaloup CRONE approximation, Charef's method etc. For discrete-time approximations, the Grunwald-Letnikoff or Tustin approximations are used. A review of approximation techniques can be found in [27], [28].

The most commonly used approximation is the CRONE (Commande Robuste d' Ordre Non Entier), which approximates the fractional operator $s^\alpha$ [28] as:

$$s^\alpha \approx C\prod_{i=1}^{N}\frac{1+(s/\omega_{z,i})}{1+(s/\omega_{p,i})} \qquad (8)$$

The approximation has N poles and N zeros, within a specified frequency band $\{\omega_l, \omega_h\}$.

$$\omega_{z,i} = \omega_l\left(\frac{\omega_h}{\omega_l}\right)^{(2i-1-\alpha)/2N} \qquad (9)$$

$$\omega_{p,i} = \omega_l\left(\frac{\omega_h}{\omega_l}\right)^{(2i-1+\alpha)/2N} \qquad (10)$$

The CRONE method adjusts the gain $C$ such that the magnitude of the expression (8) has a gain of 1 or 0 dB at 1 rad/s. Here, $N$ is the order of the approximation, and the pole and zero locations are chosen to be optimum over a chosen frequency band [29]. For discrete-time approximations, the Grunwald-Letnikoff or Tustin approximations are used [28].

### B. SOFTWARE TOOLS

With the progress of fractional calculus and its applications, numerical methods for its solution and practical implementation were also invented. These toolboxes are used for computation of fractional integrals or derivatives, Laplace transforms of fractional differential equations, etc., [30], [31]. The 'Fractional Variable Order Derivative Simulink Toolkit' by Dominik Sierociuk is a toolbox that uses the Grunwald-Letnikov definition for simulating variable and constant order fractional derivatives [32]. Another toolbox for the design of fractional order controllers was developed by Lennart vanDuist *et al.* using loop shaping techniques [33]. Some of the software tools used in fractional control are tabulated in Table 1.

### C. FRACTIONAL ORDER CONTROL

In control systems, the type of control depends on the plant and the controller. The plant and/or the controller could be of integer or fractional order. Fractional control refers to the following cases: i) IO controller for a FO plant (system equations are in a fractional differential form) ii) FO controller for an IO plant (controller is described by fractional order equations) iii) FO controller for FO plant iv) Control of a plant such that the plant has fractional dynamic behaviour [28]. Different types of fractional order controllers such as the fractional order PI/PD/PID, Tilt Proportional and Integral (TID), fractional lead-lag compensators, and CRONE controllers were discussed in [34]. Valerio & Costa discussed Fractional $H_2$ and $H_\infty$ control and fractional reset control in addition to fractional PID and sliding mode controls [28].

**TABLE 1.** Common software tools used in fractional calculus.

| Sr. No. | Software Tool | Developer | Description |
|---|---|---|---|
| 1. | FOTF (Fractional order transfer function) | Xue et al. | Control tool box for fractional order systems; uses overload programming to enable MATLAB functions to handle FO models. |
| 2. | Ninteger (Non-integer) | D. Valerio and J. Costa | Control toolbox for MATLAB for developing fractional order controllers; provides GUI for FOPID controller. |
| 3. | CRONE (Commande Robuste d'Ordre Non En-tier, meaning Non-integer-order Robust Control | Oustaloup et al. | Matlab and Simulink Toolbox for non-integer derivative applications. It can be used for the robust control of real and complex orders. |
| 4. | FOMCON (Fractional-Order Modeling and Control) | Tepljakov et al. | Combines the utilities in FOTF, Ninteger and CRONE. |
| 5. | FOPID (Fractional Order PID Controller) | Lachhab et al. | Toolbox for robust FOPID controllers. Not available for free download. |
| 6. | Sysquake | Pisoni et al. | Interactive tool for time and frequency domain performance assessment of FOPID. |
| 7. | FLOreS (Fractional-order Loop-shaping toolbox) | Lennart vanDuist etal. | Loop shaping design tool for design of fractional order controllers using frequency response data of the plant. |
| 8. | Fractional Variable Order Derivative Simulink Toolkit | Dominik Sierociuk | Simulink blocks used for simulation of fractional and variable order derivatives. Four types of Grunwald-Letnikov definition extensions are used for variable order derivatives. |

### 1) FRACTIONAL PID CONTROL

Proportional-Integral-Derivative (PID) control is one of the most widely used forms of control in the industry but has limitations under parameter variations and uncertainties [35], [36]. Fractional order PID control (FOPID) first proposed by Podlubny, gives more flexibility in the adjustment of the gain-phase characteristics and shows more robustness to gain variations. The fractional PID controller represented as $PI^{\alpha}D^{\beta}$ controller [31], [37]. The general form of the FOPID controller is:

$$C(s) = K_p + K_i s^{-\alpha} + K_d s^{\beta} \tag{11}$$

where $\alpha$ and $\beta$ are the fractional orders of the integrator and differentiator. The fractional orders in general can vary from 0 to 2. It is easily seen that $\alpha = \beta = 1$ gives the classical PID controller. With $\alpha = 0$, the fractional PD controller is obtained and further, if $\alpha = 0,\ \beta = 1$, it results in the classical PD controller. With $\beta = 0$, the fractional PI controller is obtained and further, if $\beta = 0, \alpha = 1$, it results in the integer order PI controller (Ref. Fig. 2). Thus the integer-order PI/PD/PID controllers are special cases of the fractional order. The fractional PI and PD controllers can meet three specifications. A FOPID has 2 more parameters $(\alpha, \beta)$ to tune in addition to $K_p, K_d$ and $K_i$ and hence can meet five specifications and there is more flexibility in the control [18].

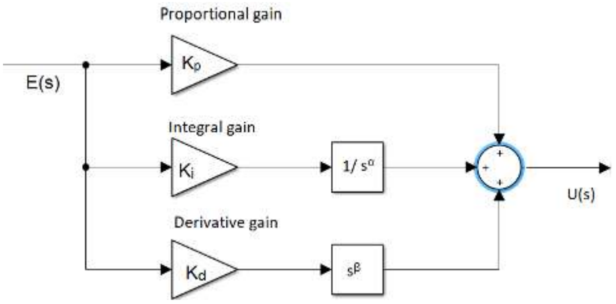


**FIGURE 2.** Fractional order PID controller [38].

Different tuning methods are explained by [28]. Meta-heuristic optimization techniques are effective and low cost options for the tuning of fractional controllers. In optimization techniques, the objective function is chosen to be minimized or maximized, according to the system specifications and requirements. The cost function can be optimized with or without constraints, depending on system requirements [39]. For a FOPID control, optimization techniques in a five-dimensional space are required. This has been made easier recently with the development of multi-objective optimization methods such as the Particle swarm optimization, Genetic algorithms (GA), Artificial Bee Colony Optimization

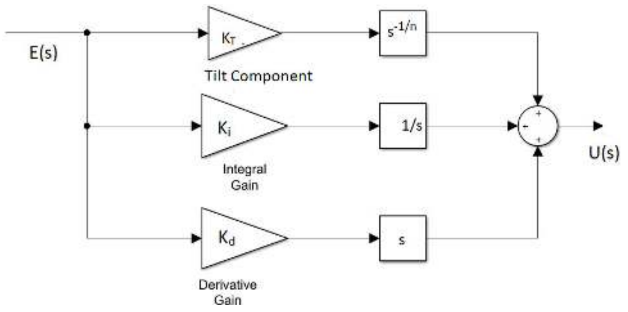


**FIGURE 3.** **TID controller [41].**

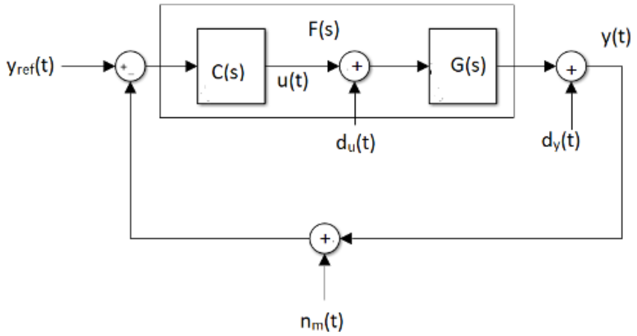


**FIGURE 4.** **CRONE controller [42].**

(ABC), combinations of fuzzy and neural network algorithms etc., [39], [40].

### 2) TID CONTROL

The Tilt-Integral-Derivative controller is obtained by replacing the proportional gain of a PID controller with a structure of the form $K_t s^{-1/n}$, called the tilt component [41] (Ref. Fig. 3). This controller gives better disturbance rejection, easier tuning and robustness to variations in plant parameters compared to the PID controller [17]. They have a higher gain before the gain cross over frequency compared to the PID controllers. As the TID controllers are very similar to the PID controllers, the same autotuning methods can be used.

### 3) CRONE CONTROL

CRONE control, proposed by Oustaloup, uses the unity feedback configuration and defines three generations of controllers. The first generation CRONE controller is used when the plant phase is constant around the gain crossover frequency $\omega_{cg}$, and only gain variations occur. It provides robustness to plant gain variations, and is defined by a bandlimited differentiator with fractional order [42]. The second generation CRONE controllers are used when the plant variations are gain-like around $\omega_{cg}$, by defining a fractional order integrator as controller around a frequency band of interest (Ref. Fig 4). The third generation CRONE controller provides robustness against other kinds of uncertainties and is defined by complex order integrator. Interested readers can refer to [43] for details on CRONE control.

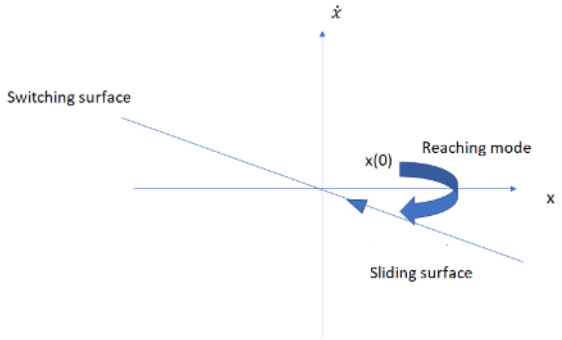


**FIGURE 5.** **Sliding mode concept [46].**

### 4) FRACTIONAL ORDER SLIDING MODE CONTROL

Sliding mode control (SMC) is a robust control technique based on variable structure systems which can be used for both linear and non-linear systems. This method forces the system trajectory to move from the initial states onto a sliding surface (reaching mode) and maintains it on this surface (sliding mode): (Fig. 5). Once in the sliding mode, the system remains on the switching line and is defined by the equation of the switching surface.

Hence the system will not be affected by parameter variations and has good stability and disturbance attenuation capability. This requires that a switching function $S = 0$ and a switching control law for the sliding mode be satisfied. For the sliding mode motion, the conditions $\lim_{S\to 0^+} \dot{S} < 0$ and $\lim_{S\to 0^-} \dot{S} > 0$ should be satisfied [44]. Switching surfaces using fractional-order control methods have been developed to improve the robustness and step response. Fractional sliding surfaces can be designed using fractional order PI,PD PID controllers ($PI^\lambda$, $PD^\mu$, $PI^\lambda D^\mu$), which have shown better performance than integer order SMC [45]. Fractional Sliding Mode Control can be designed for both integer order and fractional-order linear plants.

## *D. DESIGN AND REALIZATION OF FRACTIONAL ORDER SYSTEMS*

The fractional-order elements are non-local operators, which depends on past values, and hence the memory requirement for storing these values will be huge. Hence ideal digital realization of FO elements would require more computational resources and complexity. Hence, most of the FO systems are approximated by higher integer order transfer functions, which can work in a specific frequency range, as discussed in Section II(A). Research is going on in the field of analog realizations of fractional elements using electronics and also the manufacture of fractional elements using specific materials. Analog integrated circuit implementation of fractional elements is an attractive solution, as they are not limited by the frequency of the processor as in digital implementations, and hence are faster, and can also go for mass production.

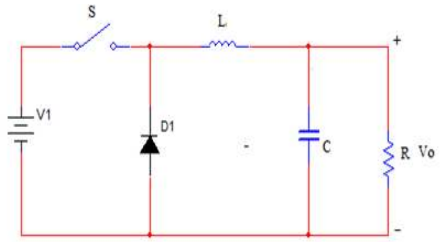
Impedances can be represented in the form of $Z = Ks^{-\alpha}$, where K is the gain, s is the Laplace variable, and

$\alpha = (0, 1, -1)$ gives a resistor, capacitor and inductor respectively. In the frequency domain, this impedance has a magnitude of $K/\omega^{\alpha}$ and a phase of $\mathrm{Arg(Z)} = -\alpha\pi/2$. For a fractional value of $\alpha$, the fractional element has a constant phase and can be called a Constant Phase Element (CPE) [47]. Such fractional elements or fractors can be manufactured using RC and RL ladder networks [48], [49]. But these networks contain many elements and are not easy to implement in integrated circuits. The properties of materials that exhibit fractional behaviour such as electrolytes, polymers etc., can be used to manufacture single component fractors [50]. A fractional capacitor obtained by using carbon Black immersed in a polymer was used to implement FO circuits in [51]. An analog implementation of FO differentiators and integrators was done using simple circuit elements and differential amplifiers and adders and was used to implement FO PI/PID controllers [52]. The fractional orders could be easily modified by changing the gains of the differential amplifiers and adders. An operational transconductance amplifier was used for the realization of a FO controller for a DC motor in [53], using CMOS technology. A review of the analog implementation of fractional elements is given by [41].

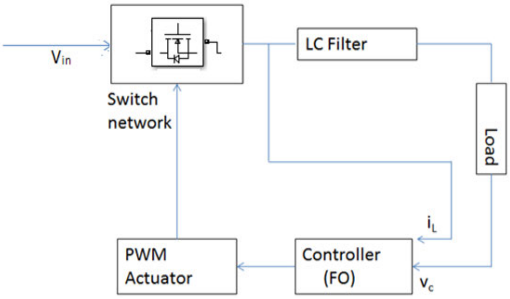
## III. FRACTIONAL ORDER CONTROL IN POWER CONVERTERS

Fractional order control has found numerous applications in power electronics in recent years. The robustness and fast dynamic response of these systems have encouraged researchers to study and develop new tools and methodologies in fractional control. Fractional order PID (FOPID) control has become an attractive option for power electronic control in the last decade. Many research papers have been published on the use of FOPI/PID in the control of a wide range of power electronic applications.

At the same time, power electronic converters can be considered to have a variable structure because of the switching action, and hence forms a suitable candidate for sliding mode control (SMC). Even though SMC is a very robust type of control, the conventional SMC experiences an oscillation about the sliding surface, a phenomenon called chattering. This is due to the switching non-linearities and parasitic dynamics [54]. Extensions of Sliding Mode Control such as Terminal Sliding Mode Control (TSMC), Higher-Order Sliding Mode Control etc. have also been used for better robust control of power electronic systems. The TSMC is a modified version of SMC, which ensures that the system states converge in finite time with improved steady-state tracking and disturbance rejection [55]. Incorporation of fuzzy and neural network strategies into SMC and TSMC have been used to enhance the robustness of active power filters and boost converters [18], [56], [57]. Fractional Order Sliding Mode Control (FOSMC) and FOTSMC gives all the advantages of SMC and additionally, can be used to reduce chattering and to improve the robustness of the system. This section describes some of the fractional control strategies used in stand-alone power converters.



(a) Buck converter



(b) Buck converter with controller

**FIGURE 6.** **Buck converter system.**

### A. FRACTIONAL ORDER CONTROL OF BUCK CONVERTER USING BODE's TRANSFER FUNCTION

Calderón *et al.* were among the first to use fractional order control (FOC) in power electronics [58]. They used fractional operators for the linear control of a DC-DC Buck converter used as a voltage compensator at a switching frequency of 2 kHz to achieve a settling time of 1 ms. The buck converter is a DC-DC switching regulator, which converts an unregulated DC voltage to a regulated DC voltage of lower magnitude at a high switching frequency [59]. The buck converter system using fractional control is shown in Fig. 6.

The authors showed that digital implementation of the fractional controller was possible and that FO control could be used for non-minimum phase systems. A FO controller was designed for the buck converter using the famous Bode transfer function of the form $K/s^{\lambda}$ [60], where input voltage variations were treated as process gain variations. A linearized discrete plant model of the system was designed, considering the LC filter and the PWM actuator as two subsystems (Fig. 6). The discrete Bode transfer function was proposed for the controller. The compensated system was represented as $F(z) = G(z)C(z) = \frac{k_c}{[\Delta(z)]^{\lambda}}$, from which the compensator C(z) could be developed. Here $\Delta(z)$ is the discrete form of the Laplace operator s. The parameters $K_c$ and $\lambda$ were selected according to the specifications of phase margin and cross over frequency. As $\lambda$ was larger than one, $\Delta(z)$ was chosen as the combination of a pure integrator and fractional integrator of order $\lambda - 1$. Approximation of the discrete fractional operators was performed by Continuous Fraction expansion (CFE) and Tustin method [61].

Simulation was carried out and an experimental prototype was implemented. The hardware prototype was implemented using a Pentium 166MHz machine for controller algorithms, and interfacing was done using the digital I/O cards PCL 818 for data acquisition and PCL 836 for PWM respectively. Both the results showed that the fractional order controller could ensure disturbance rejection with a single control loop, instead of two control loops conventionally used. The response to step voltage variations was better for the linear discrete Bode function-based controller compared to the other strategies.

### B. FRACTIONAL ORDER PI/PID CONTROL IN POWER CONVERTERS

Vanitha and Rathinakumar (2017) proposed a FOPID controller in a DC-DC buck-boost converter fed by a photovoltaic system to improve the dynamic response of the system [62]. This converter uses two MOSFET switches and a coupled inductor topology. Simulation and hardware results show reduced settling time and steady-state response with the FOPID controller.

Merrikh-Bayat used the Artificial Bee Colony (ABC) Algorithm [39] to optimize a FOPID controller for a boost DC-DC converter, which converts a fixed DC input voltage to a regulated output DC voltage of higher magnitude [63]. The boost converter has more non-linearities due to the non-minimum phase of the system and hence has to be designed carefully. The Integral Absolute Error (IAE) was chosen as the performance index for optimization. The IAE is defined as $J_{IAE} = \int_0^T |Vo - Vref|dt$. Here, $Vo$, $V_{ref}$ are the output and reference voltages respectively. The FOPID parameters are approximated by the Oustaloup recursive approximation method, where a set of recursive formulae are used in the chosen frequency band of interest $(w_L, w_H)$. The feedback control system with the FOPID controller is implemented in SIMULINK and simulated repeatedly with parameters of the controller which is optimized using ABC, until the stop criterion is reached. Results showed that the FOPID controller gave lesser settling time, better regulation and stability to step disturbances. One important result observed was that the FOPID controller required lesser on-off switching compared to the PID controller, and hence required lesser control effort. Such results bring out the advantages of the FOPID, as this would result in more energy efficiency.

Prajapati *et al.* used a dominant pole placement technique for the tuning of FOPI ($PI^{\lambda}$) controller in DC-DC buck and boost converters, which are second-order systems [64]. Settling time and overshoot were used for calculating dominant poles of the closed-loop system.

Amirahmadi *et al.* [65] proposed a method for designing optimal FOPID controllers for a boost converter by a multi-objective optimization approach. The Strength Pareto Evolutionary Algorithm (SPEA), a real parameter five-dimensional optimization approach was used to obtain a good dynamic response for a FOPID controller for a 5/12 V,15 kHz DC-DC boost converter. The CRONE approximation of order 5 was used for the FOPID. A set of optimal gains called the Pareto set was generated with the PID gains as design variables. Taking overshoot and settling time as the cost functions, a set of optimal results were generated in a look-up table, from which the designer could choose the optimal gains. This gives the user more ease and flexibility in tuning. Also, the dynamic overshoot was added as an extra objective function The start-up response optimization showed that even though the fractionality of the FO differentiator and integrator were small, it had a significant effect on the response. Experimental verification for the discrete implementation of FOPID was done using real-time simulation board dSPACE 1104 [66]. Experimental results showed a better dynamic response, robustness to variations in operating point and chaotic rejection using the FOPID compared to the integer-order PID controller. If the switching stability was chosen as the most important objective function, then chaos was removed.

Soriano-Sánchez *et al.* used another method of approximation to design a FOPID controller for a buck converter based on El-Khazali's frequency-based approach [67]. This method uses biquadratic operators to approximate $s^{\alpha} \approx T(\frac{s}{w_c})$ [68], such that it behaves like a fractional differentiator around a center frequency,$w_c$. Using the phase flatness condition, the fractional-order and the controller parameters are calculated, and adjustments are made according to the stability margins. The designed FOPID controller was found to be robust to load variations, and gave faster step response with lesser rise time and settling time compared to IOPID controllers, but had more overshoot. Practical implementation was done by analog realization, using opamps, resistors and capacitors. Approximation was carried out using the MATLAB toolbox ninteger [69].

Most of these results show that the FOPI/PID controllers have many advantages compared to the IOPID controllers, especially improved dynamic response of the system, such as lesser overshoot and settling time and stability. FOPID is an extension of linear PID, and hence would be easier to implement in industrial applications, which are dominated by conventional PID controllers. With proper tuning algorithms, FOPID controllers could be easily adapted for industry.

### C. FRACTIONAL ORDER SLIDING MODE CONTROL IN POWER CONVERTERS

Calderón *et al.* in their paper developed a fractional sliding mode control technique for the buck converter using two switching surfaces, based on FOPID and FOPI [58]. The trajectories of the sliding surfaces were generated from different bilinear model structures of the converter. A control law based on this, along with Pulse Width Modulation is applied. According to sliding mode, a switching function S = 0 has to be defined and a control law that ensures sliding motion has to be selected. A fractional sliding surface using the $PI^{\alpha}D^{\beta}$ structure was defined as:

$$S = K_p(v_r - v_c) + K_i D^{-\alpha}(v_r - v_c) + K_d D^{\beta}(v_r - v_c).$$

Here, $v_r$ is the reference voltage, $v_c$, the capacitor voltage, is the state variable, and $\alpha$ and $\beta$ are the fractional orders of the integrator and differentiator respectively. Taking the derivative, $\dot{S}$ and by substitution of the state equation for $v_c$ of the converter, expression for equivalent control is obtained. The reachability and sliding motion is ensured by applying the condition $S\dot{S} < 0$ and the equilibrium conditions. Similarly, the sliding surface was implemented using FOPI. These controllers combined the advantages of fractional control and sliding mode control. Simulation was carried out and experimental verification was done on a prototype using the Pentium 166 MHz machine for controller algorithms and interface using the PCL 818, 836 digital I/O cards. The fractional PI sliding mode controller gave the best disturbance rejection to input voltage fluctuations.

A combination of fractional order and terminal sliding mode control (FOTSMC) was proposed for a buck converter by Yang *et al.* [70]. The fractional order surface was defined as: $s = \alpha x_1^{\beta} +_{t_0} D_t^{\mu-1} x_2$. Here, $x_1$ is the output voltage error, and $x_2$ is the rate of change of voltage error, $\dot{x_1}$. Also, $0 < \mu < 1, \alpha > 0$ is a constant and $\beta = q/p$, where p and q are odd positive integers such that $0 < q/p < 1$. In the terminal sliding mode, the system converges to the terminal or equilibrium state $S = 0$ in a finite time. Substituting the parameters of the buck converter, the equivalent control law was generated. Simulation results showed that $\mu$ increased the degree of freedom, and decrease of $\mu$ gave faster output voltage response. The FOTSMC controller, in comparison with SMC and TSMC, gave a lesser steady-state error and faster response.

Zhang *et al.* designed a FOSM controller for the velocity control of a three phase Permanent Magnet Synchronous Motor (PMSM) [71]. These are AC motors that require variable frequency drives normally provided by a voltage source inverter [72]. The control objective was to sense and track the reference speed with negligible tracking error. The FO sliding surface was chosen as: $s = K_p e(t) +_0 D_t^r$, where ${}_0D_t^r$ is the fractional integral. The control law was given by: $\dot{s} = -ws - K_s sign(s)$, where $w$ and $K_s$ are positive real numbers, and sign(.) is the sign function which is equal to $\{1, 0, -1\}$ for $\{s > 0, s = 0, s < 0\}$.

Stability analysis was done using the Lyapunov stability theorem and it was proved that the system was stable for $K_p > 0$ and $0 < r < 1$ and that the system converges to the stable state in a finite time. It was also proved that the chattering observed in integer sliding mode control could be reduced with the fractional-order system. A fuzzy logic scheme was used for tuning the parameter $K_p$. Here, the reference inputs were converted to fuzzy variables using a look-up table. Simulation of the fuzzy fractional order sliding mode controller (FFROSMC) for PMSM drive was carried out with a fractional order $'r'$ of value 0.381, and compared with the integer sliding mode controller. Chattering was found to be lesser with good tracking for the FFROSMC. Robustness performance was also tested with variations in external load and motor parameters and found to be better for the FFROSMC. Experimental validation was carried out using the TI Code Composer Studio (CCS) software in PC along with TMSC320F2812 DSP controller board. The results agreed with simulation results and proved that the fuzzy fractional SMC gave zero tracking error with good disturbance rejection compared to the integer order SMC.

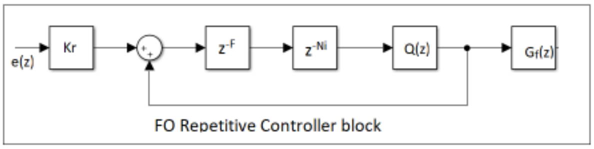


**FIGURE 7.** FO repetitive controller [73].

It is observed that the FO sliding mode controllers enhance the advantages of SMC. Further, the chattering phenomenon of conventional SMC is reduced by the FOSMC and gives good speed tracking. Implementation of artificial intelligence strategies like fuzzy, neural networks can be used for further optimization of the FOSMC parameters.

### *D. FRACTIONAL ORDER REPETITIVE CONTROL FOR PWM INVERTER*

Nazir *et al.* used Fractional Order Repetitive Control (FORC) in a PWM inverter to compensate for the harmonics and steady-state error in grid-connected systems [73]. Conventional Repetitive Control (RC) is used in power converters to obtain a steady-state error of zero in a periodic signal, and employs the signal generator in a stable closed-loop [74]. But RC depends on a known grid frequency and gives an error when the grid frequency varies due to load perturbations. A digital RC network has the form $z^{-N}/(1-z^{-N})$, where $N$ is the ratio between the sampling frequency $f_c$ and the reference frequency $f$, and is assumed to be an integer, for steady state error compensation [75]. But practically, the frequency of the grid is time-varying and hence $N$ may be fractional. As $z^{-N}$ can be implemented with integer only, it is approximated to the nearest integer value, and hence there will be deviations from the grid frequency. In conventional RC, this model is followed by a low pass filter followed by a compensator. In FORC, the fractional delay term $z^{-N}$ can be approximated by fractional delay (FD) filters, using the Lagrange interpolation method [76]. $z^{-N}$ can be written as $z^{-(N_i+F)}$, where $N_i$ is the integer part of $N$ and $F$ is the fractional part; $F = N - Ni$.

$z^{-F} = \sum_{k=0}^{n} L_k z^{-k}$; where $L_k$ is the Lagrange's coefficient.

As the interpolation order increases, the approximation error decreases. Fig 7 shows the block diagram of the FORC. The $z^{-N}$ block of the Conventional RC is split into two blocks in the FORC, with an integer and fractional component, as explained above. Here, $e(z)$ is the error signal, $K_r$ is the gain of RC, Q(z) is the low-pass filter, followed by the compensator $G_f(z)$. The output of the FORC block and e(z) are added and given to the conventional controller and plant blocks. A PWM inverter with a non-linear load was tested with FORC, using the conventional feedback controller with a plug-in type FORC controller, with a nominal frequency of 50 Hz and frequency variation from 49-51 Hz. Simulation on MATLAB and the real-time control prototype dSPACE ds1103 was used for testing the setup. It was seen that the FORC based controller gave good tracking of the sinusoidal signals with very low steady-state error. Higher-order FD filters could remove the higher order harmonics and increase tracking accuracy.

R. Nazir in his paper used the Taylor series expansion to approximate the fractional delay term in the FORC, for a single-phase PWM inverter [77]. An $M^{th}$ order series with $M + 1$ subfilters was used, where the sub-filters were designed using Lagrange''s interpolation. As the order $M$ increases, bandwidth was increased. Experimental results showed that the Total Harmonic Distortion (THD) was very low and remained constant with the proposed FORC scheme. The advantage of this method was that it was not required to redesign the filter with variation in the fractional delay parameter.

The FORC method is an attractive substitution for conventional Repetitive controllers as with some minor modifications, the existing CRC system can be made to work as FORC with much better tracking, and can be used as a solution for grid-connected systems, where a frequency adaptive design may be required.

## IV. FRACTIONAL ORDER CONTROL IN INDUSTRIAL DRIVES

Electrical drives are systems used for motion control required in many consumer and industrial applications and use electric motors as prime movers. The major components of an electrical drive are source, power converter, motor, load, sensor and control unit. The power flow from the source to the motor has to be modulated by the power converter according to the torque-speed requirements of the load [78]. It also performs power conversion from DC-AC, AC-AC etc. Various types of motors such as DC motors, induction motors, Brushless DC motors, Permanent Magnet Synchronous Motors, etc. are used in an electrical drive. The control unit controls the power modulator and various types of control can be used depending on the requirements. This section discusses Fractional order control used in electrical drive applications.

### A. FRACTIONAL ORDER PID CONTROL OF DC MOTOR DRIVES

Khubalkar *et al.* used FOPID control for a separately excited DC motor drive application and demonstrated the superiority of the fractional order PID controller over integer PID control by simulation and hardware [79]. A PWM regulated DC-DC buck converter at 20 KHz was used to control the armature voltage of the DC motor. The fractional operator $s^{\alpha}$ was approximated by an indirect discretization technique that used a constant phase value condition. Bode's phase plot was used to obtain pole-zero pairs of the FOTF, which have the same magnitude but opposite sign for slope, in order to satisfy the constant phase around $90\alpha$. Discrete-time pole-zero pairs are generated from the continuous-time values using Tustin approximation. Controller parameter optimization was executed using an improved dynamic particle swarm optimization algorithm for minimizing the Integral Time Absolute Error (ITAE). The Improved Dynamic PSO (IDPSO) is an improvisation of the PSO algorithm, where an inertia weighted factor was used in the particle velocity to speed up the process of finding the global best. The performance of the FOPID was compared with IOPID controller. The control effort was found to be lesser and speed response was faster for the FOPID controller. Hardware implementation of the circuit also was carried out using Floating-point DSP TMS320F28377S as the controller. The current consumption and input power were found to be more for the IOPID. Also, the IOPID controller lost control when tested with the same motor with different parameters. It was seen that the same FOPID controller could be used for different plants, without changing the tuning parameters and hence highlights the potential of such controllers in industrial applications.

A FOPI controller for a servomotor drive was tuned using a loop-shaping approach and approximated using the Continued Fraction Expansion method in [80]. The servomotor setup with power amplifier was tested with commands from PC in dSPACE. The ability to reject load disturbances and robustness to internal parameter variations was better for the FOPI compared to PI controller.

### B. FRACTIONAL ORDER PID CONTROL OF CHOPPER FED DC MOTOR DRIVE

Armature control of a chopper-fed separately excited DC motor drive with FOPID control was proposed by Rajashekhar *et al.* in [81]. An inner current control scheme was implemented to prevent the motor from exceeding its current limit, and the outer loop for speed control. The combined transfer functions of the FOPID controller, chopper and motor were obtained. Oustaloup's approximation of $5^{th}$ order was used to realize the fractional operators in a band-limited frequency range between $10^{-2}$ and $10^{2}$ rad/s. The Artificial Bee colony algorithm was used for tuning the parameters of the FOPID controller. The Integral Time Squared Error (ITSE), the weighted sum of ITSE and the Integral squared Controller Output (ISCO) were considered as objective functions. The function ITSE ($J_1 = \int_0^{\infty} te^2(t)dt$) was used for minimizing the overshoot and settling time. But as this criterion was prone to cause integral wind up and saturation of the actuator for sudden set-point changes, it was compensated by using the weighted term $J_2 = \text{ITSE} + \text{ISCO} = \int_0^{\infty}[w_0 te^2(t) + w_1\, u^2(t)]dt$. Here the weights $w_0, w_1$ are used to balance the effect of control error and action. The setup was tested with both IOPID and FOPID controllers using $J_1$, $J_2$ and their combinations respectively. It was seen that the FOPID with $J_1$ function gave no overshoot and very less settling time. This controller gave good robustness compared to the IOPID when gain was varied. When tested with $J_2$, the FOPID controller gave better speed tracking and better Gain and Phase Margin.

### C. DIGITAL FRACTIONAL ORDER PID CONTROL OF FOUR QUADRANT CHOPPER FED DC MOTOR DRIVE

A two-degree freedom FOPID controller was proposed in [82] for the speed control of a four-quadrant chopper-fed DC motor drive. The two DOF controller is obtained by applying a prefilter f(s) on the reference input r(s) and comparing f(s) with the feedback signal from the output, and then applied to a 1-DOF controller C(s). The controller C(s) and prefilter f(s) are given by

$$C(s) = K_p + \frac{K_i}{s^{\lambda}} + \frac{K_d s^{\mu}}{1 + \frac{K_d s^{\mu}}{K_p M}} \tag{12}$$

$$f(s) = K_p a + \frac{K_i}{s^{\lambda}} + \frac{K_d s^{\mu}}{1 + \frac{K_d s^{\mu}}{K_p M}} b \tag{13}$$

Here, $\lambda$ and $\mu$ are positive real numbers, M is the filter coefficient and a, b are the weights of set-points. The fractional orders are approximated by the alternate placement of pole-zero pairs on the real axis. Tustin method was used for discretization, and the IDPSO method was used for optimization. The control system was implemented on the DE2-115 FPGA board, and performance was compared with FOPID and IOPID controllers. Control effort was tested using performance indices and found to be much lesser for the 2-DOF FOPID compared to PID. The transient performance was also better and faster.

### D. FRACTIONAL ORDER PID CONTROL OF BRUSHLESS DC MOTOR DRIVES

Brushless DC (BLDC) motors are very durable, efficient motors with high power density and a good speed range, and hence used in the automotive industry, consumer applications etc. They have a permanent magnet rotor and a stator wound with copper windings to get a trapezoidal back emf. BLDC motor drive comprises of the motor, power drive and control circuit and sensors [83]. PID control is used widely in BLDC drives. The application of FOPID to BLDC motor drives has been explained below.

An optimized FOPID controller was used for a sensorless BLDC motor drive using ABC, Modified GA and Bat algorithm [84]. Normally, Hall effect sensors are used to sense the rotor position for synchronizing the stator and rotor in BLDC motor drives. But this is costly and adds to the size of the system. In the proposed sensorless technique, the error between the reference and estimated rotor speed is obtained from the error in the current. This is amplified and gives the torque component of the stator current. The model of the BLDC with the optimized FOPID was simulated and transient and steady-state specifications were tested.

An FOPID controller was used for the speed control of a Permanent Magnet BLDC motor drive [85]. The inner loop for current and outer loop for speed is controlled by FOPID and IOPID separately for comparison. The RMS phase current was significantly reduced using FOPID controller. The system was implemented using FPGA-in-loop. The overshoot and settling time is reduced, and the control effort was greatly reduced with FOPID.

A metaheuristic Bat algorithm was used by the authors [86] for the tuning of a FOPID controller for the rotor speed control of a sensorless BLDC motor drive and compared with the ABC and Modified Genetic Algorithm.

A FOPID controller tuned with Real coded genetic algorithm (RGA) and Bio-geography based optimisation (BBO) was used for a BLDC for an electric vehicle. The performance comparison of FOPID with PID controller showed 50% improvement in transient response performance [87].

A half derivative term was added to the PD controller in [88] to design a $PDD^{\frac{1}{2}}$ controller which was used in the position control of a BLDC for improving the tracking performance. This was found to be an easy and cost-effective solution and could be easily implemented in commercial drives.

### E. FRACTIONAL ORDER PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVES AND INDUCTION MOTOR DRIVES

A fractional order PI controller was used for a Permanent Magnet Synchronous Motor (PMSM) drive by Thakar *et al.* by frequency domain design using two methods, based on a linear model of the motor [89]. The first was the intersection method based on the iso-damping property and the second method was a robustness index based on Nyquist plots. Three FOPI controllers were used for the vector control of a nonlinear simulated model of the PMSM. Two FOPI controllers were used for the d and q axis current control, and the third for the outer speed control loop. A better robustness index was obtained for the Nyquist based method, but with increased control effort.

A Fractional order PI controller with an IO/FO prefilter was designed for electrical drives with Permanent Magnet DC (PMDC) and Permanent Magnet Synchronous motors [90]. The motors were modeled as first order systems with delay. The feedback system was designed using closed-form formulas, and tuned using the symmetric optimum method. The dynamic response for the FOPI controller with FO prefilter is better and shows better disturbance rejection and the FO prefilter cancels the oscillations. Fractional orders of 1.4,1.5 and 1.6 are used. The PI controllers have lesser rise times, but show more oscillations.

A Fractional order SMC was used for the Speed control of PMSM and gave good speed tracking, disturbance rejection, less chattering. This controller gave lesser current spikes at sudden increase of load, lesser q-axis component current ripple from SMC [91].

A Fractional-order PI controller was designed for speed regulation of an induction motor drive and compared with an Integer-order PI controller [92]. The system was tuned using

**TABLE 2.** Classification of papers based on fractional order control in power converters and drives.

| Type of Fractional controller | Application | Optimization/Analytical method | Remarks | Reference |
|---|---|---|---|---|
| FO controller based on Bode transfer function | Buck converter for standalone applications | Application of different fractional control strategies and digital implementation without using optimization | Experimental verification and comparison of various methods | [58] |
| FO PID controller | PV Controlled Buck-boost converter | No | Hardware implementation,comparison with linear PI | [62] |
| FOPID controller | Boost converter | ABC algorithm | Simulation, comparison to PID | [63] |
| FO PI controller | Buck and Boost converters | Dominant pole placement technique | Simulation,comparison with linear PI | [64] |
| FOPID controller | Boost converter | SPEA optimization | Hardware implementation done using dSPACE and comparison with PID | [65] |
| FOPID controller | Buck converter | Approximation using bi-quadratic operators | Analog implementation and comparison to PID | [67] |
| FOPID control | DC motor drive with Buck converter | IDPSO optimization | Hardware implementation with DSP controller,comparison with PID | [79], [82] |
| FOPID controller | Chopper fed DC motor drive | ABC optimization | Simulation on MATLAB, comparison with PID | [81] |
| FO PI controller | Servomotor Drive | Designed using Loop shaping and CFE | Experimental validation using dSPACE | [80] |
| FOPID controller | BLDC drive | Analytical Method | Implementation in FPGA-in-the loop | [85] |
| FOPID controller | Sensorless BLDC drive | ABC, Bat algorithms | Simulation, comparison with PID | [84], [86] |
| FOPID controller | BLDC drive | Real coded genetic algorithm (RGA) and Bio-geography based optimisation (BBO) | Simulation | [87] |
| FO $PDD^{\frac{1}{2}}$ controller | BLDC drive | Method | Simulation and experimental verification | [88] |
| FO PI controller | PMSM Drive | Design using Bode and Nyquist frequency domain methods | Simulation | [89] |
| FO PI controller | Induction motor Drive | Fractional MIGO | Simulation and experimental validation | [92] |
| FOSMC | Buck converter for standalone applications | Application of FOPI and PID sliding structures and digital implementation without using optimization | Experimental verification | [58] |
| FO Terminal SMC | Buck Converter | Analytical method | Simulation, comparison with conventional SMC and Terminal SMC | [70] |
| FO SMC | Inverter for Three phase Permanent Magnet Synchronous Motor control (PMSM) | Parameter fuzzy autotuning method | Experimental verification using TI Code Composer studio and DSP controller | [71] |
| FO SMC | PMSM drive | Design with FO differentiation and integration | Experimentation using dSPACE | [91] |
| FO repetitive control | PWM inverter | Analytical design | Experimental validation using dSPACE | [73] |
| FO repetitive control | PWM inverter | Taylor series expansion to approximate fractional delay | Experimental validation | [77] |

Fractional order-Maximum Sensitivity Constrained Integral Gain(FO-MIGO) method. The drive system was tested for square wave tracking, and the overshoot was negligible for the FO-PI controller. Also, the torque/output was better for the FO-PI and has good disturbance rejection with lesser control effort.

These applications show that the FO controllers employing multi-objective optimization techniques can be effectively used in industrial drives and can give cleaner and more energy-efficient systems.

Various Fractional order controllers implemented for power converters and drives are tabulated in Table 2.

## V. FRACTIONAL CONTROLLERS IN RENEWABLE ENERGY SYSTEMS

The ever-growing demand for energy, climatic changes and the strive for a greener planet has resulted in greater utilization of various renewable energy sources like solar, wind, tidal, geothermal energy sources etc. But the availability of these resources follow seasonal patterns and also there may be fluctuations in the load demands. Hence, power electronic interfaces are required between these resources and the power system for effective power management. A very good review of the use of power electronic systems in renewable energy is given by Iov *et al.* [93].

### A. PHOTO-VOLTAIC SYSTEMS

Solar energy has received considerable attention among renewable energy sources due to its easy availability, less maintenance and pollution-free quality. This has resulted in rapid development of photovoltaic (PV) systems for power production in the recent decades.

A Photovoltaic (PV) system uses interconnected PV panels with several solar cells, which convert the incident energy to electrical energy. This electrical energy can be used to supply power to devices or charge a battery. But the output power of PV systems changes with climatic conditions like irradiance (G) and temperature and is non-linear. According to the Maximum Power Transfer Theorem, matching of load and source impedance is required. Hence a DC-DC converter is required for load matching, which is achieved by duty cycle adjustment [94]. To operate the PV system optimally, the Maximum Power Point (MPP) has to be calculated and tracked so that the operating point is as near to the MPP as possible [95], [96]. This is achieved by an MPP Tracking (MPPT) system, which controls the power electronic interface between the PV system and the load. To utilize the power generated at night also, a battery bank is required as backup. A switched-mode DC-DC converter is mostly connected at the output of the PV panel and converts the varying voltage to a constant voltage required to charge the battery load. The duty cycle of the converter is varied using PWM by the MPPT algorithm to get the maximum possible output from the PV panel [97]. A PV inverter converts the DC to a fixed AC output for AC loads. A typical PV power system is shown in Figure 8.

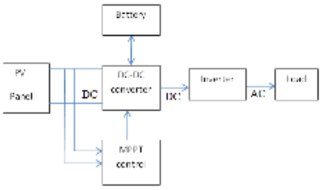


**FIGURE 8.** Block diagram of a typical PV system.

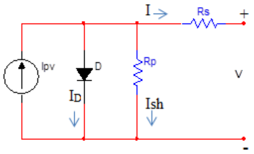


**FIGURE 9.** Model of solar PV cell.

The solar cell is a semiconductor structure of crystalline silicon, which can be modeled as a single photocurrent source. A diode with two resistors is used to represent the non-linearities inside the PV cell. The single diode model of a PV cell is shown in Figure 9 [97]. It is seen that the current generated by the solar cell depends on temperature and irradiance [98].

Some of the common MPPT strategies are Perturb and Observe (P&O), Incremental conductance (INC), soft computing techniques such as fuzzy control, Artificial Neural networks, Genetic Algorithms etc., [99]. Recently, fractional order methods have been incorporated into the conventional MPPT techniques and are seen to be very effective due to their robustness to non-linearities and transients. Kamal & Ibrahim gives a comprehensive review of conventional and fractional order MPPT techniques [97].

#### 1) FRACTIONAL-ORDER INC METHOD FOR MPPT CONTROL

Kuo-Nan Yu *et al.* proposed a Variable fractional Order Incremental Conductance Method for MPPT control of a DC-DC boost converter [100]. As the solar cell is a semiconductor material, its output power is nonlinear and is influenced by temperature. This was represented by a fractional order $\alpha$. The conventional Incremental Conductance (INC) method evaluates the condition

$$\frac{dP}{dV} = 0$$

which corresponds to MPP. Here P,V and I are the power, voltage and current respectively. The algorithm adjusts the duty cycle of the DC-DC converter till the condition

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0$$

is satisfied.

Instead of the conventional derivative, a fractional order derivative of order $\alpha$ is used to represent the diffusion phenomena for varying temperatures. The fractional differentiator was defined using the RL derivative [100].

$$\frac{d^{\alpha}I}{dV^{\alpha}} = \frac{I - \alpha I_0}{(V - V_0)^{\alpha}}$$

Here, $I_0$ and $V_0$ are the previous values of current and voltage respectively. The slope is a straight line for $\alpha = 1$. For $0 < \alpha < 1$,

$$\frac{d^{\alpha}}{dV^{\alpha}}\left(\frac{-I_0}{V_0}\right) = \left(\frac{-1}{V_0}\right)\frac{d^{\alpha}I_0}{dV^{\alpha}} + (-I_0)\frac{d^{\alpha}{V_0}^{-1}}{dV^{\alpha}} \quad (14)$$

This can be expanded using the fractional derivative formula of (15).

$$D_t{}^{\alpha}t^m = \frac{\Gamma(m+1)}{\Gamma(m+1-\alpha)}t^{m-\alpha} \quad (15)$$

As the FO differentiator curve can approximate the MPPT effectively, the steady-state tracking is faster and transient MPPT response is also good. The value of $\alpha$ is initially kept 1, (conventional INC tracking) and then slowly varied as the MPP is nearing. The Extenics Variable Step Size (EVSS) control is also used with variable fractional order INC, to increase or decrease the offset voltage $\Delta$V in variable step size. To reduce voltage perturbation around the MPP, a reference frame is used for voltage, power and slope so that the minimum step size is used near the MPP for perturbation. This improves the stability, tracking speed and overall efficiency. Simulation was performed for varying irradiance levels from 200 kW/$m^2$ to 1000 kW/$m^2$ at temperature 25°C and executed for INC, Fractional-order Incremental Conductance (FOINC) and Variable Fractional-order Incremental Conductance (VFOINC) with EVSS. The transient and steady-state responses were found to be better for the proposed scheme.

#### 2) FRACTIONAL OPEN CIRCUIT VOLTAGE ALGORITHM FOR PV MODULE

A fractional open-circuit voltage (FOCV) based algorithm was proposed for evaluating the performance of a High Concentration PV (HCPV) module with a buck converter by Huang and Hsu [101]. The HCPV module used high-efficiency triple-junction solar cells (TJSC) made of III-V compound semiconductor materials [102]. The TJSC can be modeled by connecting the three single diode models in series which can be represented by: $V_{cell} = \sum_{i=1}^{3} V_i$; for i = 1, 2, 3.

$I_{cell}$ can be written using the summation of the current equation for the single solar cell. The open-circuited voltage $V_{oc}$ can be obtained by setting $I_{cell} = 0$. The HCPV module was modeled in MATLAB / SIMULINK using a single TJSC model. The power of the HCPV module was expressed as a function of irradiance, air mass, temperature and wind speed. The FOCV technique makes use of the relationship between the peak voltage ($V_m$) and open-circuited voltage ($V_{oc}$) as $V_m = KV_{oc}$, where the proportionality constant K depends on irradiance conditions and is around 0.89. The operating voltage $V_m$ is obtained by multiplying K with $V_{oc}$. The operating current $I_m$ at $V_m$ is measured and their product gives maximum power.

The MPPT algorithm was applied to a buck converter which conditions the power from the HCPV module to meet the load requirements and also matches the I-V curve with the output load. The duty cycle of the buck converter was varied by the MPPT controller to achieve impedance matching between the module and load and to track the MPP. Simulation and comparison with the P&O algorithm were carried out under irradiance and temperature variations, keeping one of the parameters constant while the other was varied. It was seen that the tracking efficiency under the two scenarios was better with the FOCV method. The dynamic response and tracking speed were also found to be better.

#### 3) FOINC BASED MPPT CONTROL OF BOOST CONVERTER

A FOINC based MPPT strategy with optimal parameters was used for the control of a boost converter in a PV system by Al-Dhaifallah *et al.* in their paper [103]. The PV panel was modeled using the single diode model. The boost converter duty cycle for MPPT was calculated as

$$D_m = 1 - \frac{V_m}{\sqrt{P_m R_L}}$$

where $V_m$ and $P_m$ correspond to the PV panel voltage and output power at MPP respectively, $R_L$ is the boost converter output resistance. According to the INC method, dp/dv = 0 at MPPT. The error signal was calculated as:

$$e = \frac{1}{V}\frac{dP}{dV} = \frac{I}{V} + \frac{dI}{dV} \quad (16)$$

The duty cycle control is done by the controller to make the error zero such that:

$$D_{new} = \begin{cases} D_{old} + K^{\alpha}e, & if\ e > 0 \\ D_{old}, & if\ e = 0 \\ D_{old} - K^{\alpha}e, & if\ e < 0 \end{cases} \quad (17)$$

Here, $K$ and $\alpha$ are the gain and order of the fractional integrator respectively. The transfer function of the system was found by the small-signal analysis of the boost converter with the PV system. The error signal was linearized around $V_m, I_m$ using the Taylor series. The Radial Movement Optimizer with the root locus technique was used to optimize the parameters K and $\alpha$ of the FO integrator such that the energy cost function was maximized, and stability analysis was done. Simulation of the PV system using the FOINC method ensured fast dynamic response and tracking accuracy under varying climatic conditions.

#### 4) PERTURBATION OBSERVER-BASED FOPID CONTROL OF PV INVERTER

A photovoltaic inverter was controlled using a perturbation observer based Fractional PID (POFOPID) method and optimized using Yin-Yang technique (Yang *et al.*) [104]. Perturbation methods require some variations in the control variable for determining tracking conditions. The PV inverter converts the DC from the solar panel to AC for supplying to a grid or local utilities. The PV panel is formed by series and parallel combination of many PV modules. A three-phase grid-connected PV inverter with balanced conditions was used and the three-phase parameters were converted to d-q axis parameters by Park's transformation as shown:

$$v_d = e_d + Ri_d + L\frac{di_d}{dt} + \omega L i_q \tag{18}$$

$$v_q = e_q + Ri_q + L\frac{di_q}{dt} - \omega L i_d \tag{19}$$

Here, the subscripts d and q denote the direct and quadrature axis components of the grid voltage (e), grid current(i), and inverter output voltage (v), respectively, and R and L being the resistance and inductance of the grid. The PV inverter non-linearities, atmospheric fluctuations, disturbances etc. were accumulated into a perturbation, which was estimated by a high gain state perturbation observer (HGSPO) and compensated by a FOPID controller.

The FOPID had the integrator order $\mu$ and differentiator order $\lambda$ between 0 and 2. State space equations of the PV system were written and two perturbation parameters were defined and estimated by a second and third order HGSPO. The POFOPID controller was defined and optimized by Yin-Yang Pair Optimization [105]. The optimization minimizes the tracking error, the q-axis current and the overall control costs. The controller was applied to a grid-connected PV inverter under variations of four parameters, i.e., solar irradiation change, temperature variation, power grid voltage drop and inverter parameter uncertainties. Simulation in MATLAB / SIMULINK was carried out for PID, FOPID, feedback linearization control (FLC), SMC and the POFOPID controller for comparison. The proposed controller gave the fastest tracking and lowest overshoot and minimal control costs. An experimental setup was executed on the dSPACE based Hardware-in-the-loop (HIL) platform DS1006 for the inverter circuits and sensors and transmitted to the PO-FOPID controller on the DS1004 board to validate the feasibility of implementation. The PO-FOPID controller was compared with PID, SMC, FLC, and gave the lowest fitness function IAE. The combination of the FOPID, which improves the robustness and the dynamic performances, and the perturbation control due to the PO mechanism gives the least control effort. Comparison with various controllers show reduced settling time and overshoot but at the cost of higher complexity, and will have to be a compromise between the cost and computational burden and the improved performance of the system.

### 5) PASSIVITY-BASED FOPID CONTROLLER FOR GRID-CONNECTED PV INVERTER

A passivity based FOPID controller was also designed by Bo Yang *et al.* for a grid-connected PV Inverter [106]. Passivity based controllers (PBC) treat the dynamic system PV as an energy transforming device. Here, a complex system was decomposed into simpler sub-systems and their local or distributed energies were added up to determine the system behaviour using a storage function. The PBC tries to make a system passive with a storage function that has a minimum at the equilibrium point. The controller was also considered to be a separate dynamic system. The PV array was connected to the PV Inverter, controlled by the spatial vector PWM. The grid parameters were converted to $d-q$ parameters as shown in equations (18) and (19).

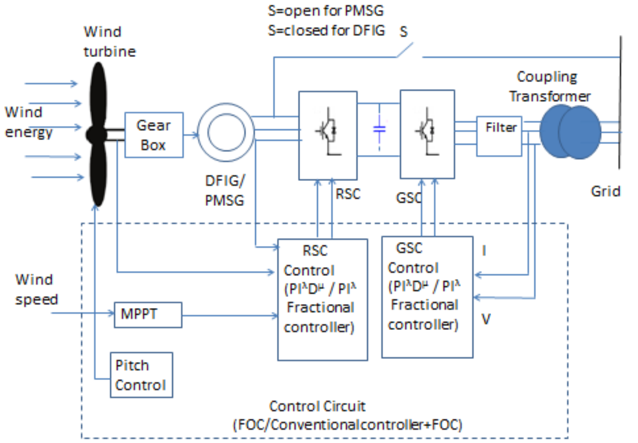


**FIGURE 10.** Block diagram of a wind energy conversion system with fractional control.

The FOPID parameters $\lambda$, $\mu$ could significantly tune the dynamics. Optimization was done by the Grouped Grey Wolf Optimizer, which simulates the hunting mechanism of grey wolves to attain the optimal point. The PFOPID controller parameters were tuned and tested under climatic condition variations and power grid voltage drop to minimize the DC link voltage tracking error, the quadrature-axis current and the control costs. Energy reshaping can be done by carefully tuning the FOPID control parameters to increase the rate at which the storage function decreases, to improve the dynamics of the closed-loop system. Simulation results showed that under a power grid voltage drop to 0.4 p.u (per unit) for 150 ms, the PFOPID restored the active power and DC link voltage at the fastest rate. Hardware implementation using dSPACE based HIL simulator also gave results matching with simulation.

## B. WIND ENERGY CONVERSION SYSTEMS

A typical wind energy conversion system (WECS) uses a wind turbine with rotor blades, which performs kinetic-mechanical energy conversion. The turbine is connected on the same shaft to a generator, which could be AC or DC. The DC generators are normally used for small homemade wind turbines and are small in size, cheaper and run at lower speeds. The AC generators can be synchronous or induction type, the commonly used ones being the Permanent Magnet Synchronous Generator (PMSG), Doubly fed Induction Generator (DFIG) and the Wound rotor Induction Generator [107].

Power electronic converters are required for converting the generated AC power to the required grid voltage and frequency. The AC output of these generators can be rectified to DC with a rectifier unit and then converted to AC of proper voltage and frequency by using an inverter. In some cases, an AC-AC generator can be directly used instead of the AC-DC-AC conversion [108]. Power converters convert the variable frequency to fixed frequency, and also can be controlled to make the wind turbine operate at the maximum power point at various shaft speeds. Hence the precise modeling and control with harmonic analysis of the power converters and the wind turbine system are very crucial. The development of fractional calculus in recent years has seen a considerable increase in the use of fractional order control in wind energy systems. A typical wind energy conversion system block diagram is shown in Figure 10.

#### 1) FRACTIONAL-ORDER CONTROL OF VARIABLE-SPEED WIND TURBINE

R. Melicio *et al.* in their paper developed a fractional PI-based strategy along with sliding mode control for a variable-speed wind turbine with PMSG and discussed its use on the matrix (AC-AC) converter and multilevel (AC-DC-AC) converter topologies [109]. An integrated model of the wind turbine system was developed with a variable speed turbine, two-mass drive train model, PMSG and two power converters. Matrix converter can convert the variable AC from the generator to constant AC for the grid and uses nine bidirectional IGBT switches [110]. A three-phase active network was used for modeling the network and state space equations were written for the network and the respective converter [110]. A fractional $PI^{\mu}$ controller is used which is controlled using space vector PWM associated with sliding mode. The sliding mode strategy ensures that the system slides on the surface s such that $ds/dt < 0$ and subject to a small error within defined limits. Fourier analysis was done and discrete Fourier Transform (DFT) was used to compute the harmonic behaviour. Simulation results showed that the multilevel converter topology had very less THD and had a better performance. The THD level was less than 5% for both the converter topologies due to the fractional control.

Another paper [111] used the isodamping feature of fractional order systems by designing a robust FOPI controller for a wind turbine with a PMSG using analytical methods. The results were compared with integer PI controller. The simulation results showed that the backlash normally observed in such systems was eliminated by the FOPI controller, whereas the integer PI controller was not able to track the input commands properly.

#### 2) OFFSHORE WIND TURBINE FRACTIONAL CONTROL STRATEGY

Offshore wind energy systems are built on water bodies like oceans, where the wind speeds are much greater than onshore and are already being used in many countries. D M. Seixas *et al.* proposed a fractional control strategy for an offshore wind turbine equipped with a PMSG and a back-to-back Neutral Point Converter (NPC) [112]. This converter was used to convert the variable injected frequency into a constant frequency. As offshore systems have increased rotor dimensions and bigger turbines, the drive train system was considered as a five-point mass model. A back-to-back NPC three level converter was used which had twelve unidirectional IGBTs working as a rectifier and twelve identical IGBTs operating as an inverter. Each level is formed by four IGBTs connected in the same phase.

A four-level converter topology with eighteen IGBTs for the rectifier and eighteen for the inverter was also studied. Fractional PI controller with sliding mode and space vector PWM was used. The power converters were modeled as a delay and a second order transfer function was used for the modeling of left-over dynamics. The $PI^{\mu}$ controller determines the stator currents from the difference between the voltage $v_{dc}$ and the reference voltage $V_{dc}$. The error $e$ between the stator current and the reference stator current is processed by the sliding mode control strategy. Simulation of the offshore WECS with three and four level converters were implemented on MATLAB. The use of the FOPI controller enables the injection of an almost three phase sinusoidal current into the grid. the harmonic assessment showed low values of THD for both types of converters.

#### 3) FRACTIONAL CONTROL OF VARIABLE-SPEED WIND ENERGY SYSTEM CONNECTED TO GRID

A fuzzy fractional order PI+I controller (FFOPI+I) was implemented by Beddar *et al.* for a variable speed grid connected wind energy system with PMSG [113]. The controller was effective in maximum power point tracking and unity power factor control. The fuzzy control changes the integral gains at run time and hence makes the system more adaptive. A machine side power converter is an AC-DC converter used to extract the maximum power point under variable wind speeds and is controlled by vector control, using an inner PI controller and outer FOPI controller. The Grid side converter is a DC-AC converter used to obtain sinusoidal currents for the grid with good power quality. The FFOPI+I controller was implemented by using the fuzzy logic controller (FLC) in parallel with the FOPI and PI controllers. The output is the sum of the outputs of PI and FOPI controllers. PSO algorithm was used for the optimization of the FOPI parameters. The performance of the proposed controller was tested with an experimental setup. The wind turbine was emulated using a DC motor and used to control the PMSG. The experimental results showed good tracking and fast transient response with low overshoots. Sinusoidal grid current with a THD of 4% was obtained with a power factor of 0.99.

#### 4) FRACTIONAL-ORDER SLIDING MODE CONTROL OF PMSG WITH ENHANCED POWER QUALITY

Xiong *et al.* [114] proposed a FO sliding mode controller for a PMSG to regulate the active and reactive powers. Two sliding mode controllers were designed for the RSC and GSC. The sliding surface was defined as:

$$S = e + \wedge * D^{\alpha-1}(sig(e)^{\gamma}) \tag{20}$$

Here, e is the error between desired and measured quantity, $\wedge$ is a positive definite diagonal matrix, $D^{\alpha-1}$ is a Caputo fractional derivative of order $\alpha - 1$, and $sig(e)^{\gamma} = |e|)^{\gamma} sgn(e)$ and $sgn(e)$ is the sign function of $e$.

The reaching law was obtained as $\dot{S} = F(S)$, where F(S) is a function of S. The optimal angular velocity obtained using MPPT was used to track the actual velocity of the PMSG by the machine side controller. The actual and desired d-axis stator currents were also used as control inputs. The grid-side controller was used for controlling the DC link voltage and the output grid side voltage. A Lyapunov stability analysis was done and optimal controller parameters were obtained with the Gravitational Search Algorithm. The ISE performance index was compared with SMC and PI control, and was found that the FOSMC gave lesser ISE. Further, it was shown that the chattering which occurs in sliding mode control is overcome in FOSMC, and gave more robustness with good tracking.

#### 5) FRACTIONAL CONTROL IN A WIND TURBINE WITH DOUBLY-FED INDUCTION GENERATOR

Mahvash *et al.* used Fractional order [PI] controller for the rotor side converter (RSC) of a DFIG connected to a wind turbine [115]. The FO[PI], defined as $K_p + K_i/s^{\lambda}$, where $\lambda$ is between 0 and 1, was implemented using the discrete integer PI controller merged with a tracking block to consider the order $\lambda$ [116]. The FO[PI] controller was designed using the frequency response specifications of phase margin, robustness to gain variations and gain limitation at $\omega_c$ [117]. The stator of the DFIG is connected to the grid, and the rotor side is connected through slip rings to a back-to-back converter. This converter has a Rotor Side Converter (RSC), which converts the AC power generated by the rotor side of DFIG to DC and a Grid Side Converter (GSC), which performs DC-AC conversion and is connected to the grid. The RSC controls the active and reactive powers, whereas the GSC kept the DC link voltage constant irrespective of variable wind speeds. The active power, rotor speed and currents of the DFIG were improved by the use of the FO[PI] controller. The controller was used in the outer loop for active power control and the inner loop for rotor current control according to the principle of stator voltage orientation. The effect of grid parameter uncertainty was tested with parameters like the short circuit capacity and $X/R$ ratio. Simulation results showed the superiority of the FO[PI] controllers over the PI controllers.

Mahvash *et al.* also proposed a FOPI control scheme in a DFIG in a 10 MW wind farm for the pitch compensation control of the DFIG [118]. M.Asghar *et al.* compared the performance of a fault-tolerant fractional and integer controller for DFIG control [119].

#### 6) FRACTIONAL-ORDER SLIDING MODE CONTROL IN DFIG BASED SYSTEMS

Ebrahimkhani proposed a robust fractional-order Sliding mode controller for the MPPT of a DFIG wind turbine [120]. This controller had the advantage that the uncertainty bounds were not required to be known, and also it eliminated chattering. Performance comparison with PI controller showed faster speed tracking with almost no tracking error, and better regulation of reactive power. Li *et al.* designed a Direct torque control scheme with FO Sliding mode controller for a DFIG based windfarm [121]. The proposed control scheme was used to reduce the effect of subsynchronous resonance and interaction due to the series compensators in wind farms [122]. The controller parameters were tuned using the Genetic Algorithm. The proposed controller was compared with the existing schemes like the Sub-synchronous damping control (SSDC) and Terminal SMC used for mitigation of the subsynchronous interaction, and was found to give faster damping, more robust performance and lesser chattering. An experimentation setup using TMS320F2812DSP for DFIG control and the dSPACE platform for RSC control verified the simulation results.

A FOSMC scheme was designed for the Grid side converter for a DFIG based wind farm by Li *et al.* [123]. The feedback linearization technique was used to linearize the system and the FOSMC was applied to the Grid side converter to reduce the subsynchronous control interaction (SSCI) occurring in wind farms controlled by DFIG. The Riemann Liouville (RL) definition was used for the fractional derivatives. It was found that the proposed controller reduced SSCI in lesser time compared to the conventional Vector control, Feedback Linearization SMC and High-Order SMC.

All these showed the superiority of fractional order control over conventional control. Table 3 summarizes the applications of fractional order control in PV and wind energy systems.

### *C. SMART GRIDS AND MICROGRIDS*

Smart Grid is a new concept of modern power systems, which focuses on more efficient, reliant and faster grid structures that have alternative and renewable energy sources integrated with modern control and communication systems. Such a system involves the interconnection of various components of the grid to the transmission, distribution, substations and consumers using sensors and communication networks [3], [125]. Distributed generators, and energy storage elements and load demand management form the focus of these smart grid structures. Such systems have lots of uncertainties due to the sudden load fluctuations and parallel distribution and generation.

On the other hand, a microgrid is a distributed energy system, which can be considered to be a localised energy grid, typically connected to the main grid but can be automatically disconnected and work as a stand-alone system (See Fig. 11). It can function on its own to supply customers in the

**TABLE 3.** Classification of published papers based on fractional order control in PV and Wind energy conversion systems.

| Application | Type of Fractional controller | Type of power converter/System | Remarks | Reference |
|---|---|---|---|---|
| PV applications | FOINC, FOVSS, FOESC, FOSMC | Various power converters | Review of conventional and fractional order MPPT techniques | [97] |
| PV applications | Variable FO INC | Boost converter | MPPT control, comparison with INC, FOINC | [100], [103] |
| PV application | FO OCV | Buck converter | MPPT control of a High Concentration PV module, compared with P&O | [101] |
| PV applications | Perturbation observer based FOPID | PV inverter | MPPT control, controller optimization using Yin-Yang technique | [104] |
| PV applications | Passivity based FOPID controller | Grid connected PV inverter | MPPT control, controller optimization using grouped grey wolf optimizer | [124] |
| Wind energy system with PMSG | FOPI along with sliding mode control | Matrix and multilevel converters | Variable speed operation of wind turbine with better power quality, comparison with PI | [110] |
| Wind energy system with PMSG | FO sliding mode control | RSC and GSC | Gravitational Search algorithm used for optimization, comparison with PI and SMC | [114] |
| Wind energy system with PMSG | FOPI along with sliding mode control and space vector PWM | Back to back Neutral Point converter (NPC) | Off shore wind turbine equipped with a PMSG, evaluated the THD of current injected into grid with a five mass-model | [112] |
| Wind energy system with PMSG | Fuzzy fractional order PI+I controller | AC-DC machine side converter and DC-AC GSC | MPPT and unity power factor control of system with PMSG | [113] |
| Wind energy system with DFIG | FO[PI] controller | Back to back converter | DFIG with grid connected stator and rotor side connected to back-to-back converter and Frequency domain analytical design, comparison with PI | [115] |
| Wind energy system with DFIG | FOPI controller | Back to back converter | Pitch compensation control of DFIG | [118] |
| Wind energy system with DFIG | FO Sliding mode controller | Back to back converter | Wind turbine with DFIG | [119], [120] |
| Wind farm with DFIG | FO Sliding mode controller | Rotor side converter | Tuning using GA,comparison with SSDC and Terminal SMC | [121] |
| Wind farm with DFIG | FO Sliding mode controller | Grid side converter | Comparison with Vector control,FL and High order SMC | [123] |

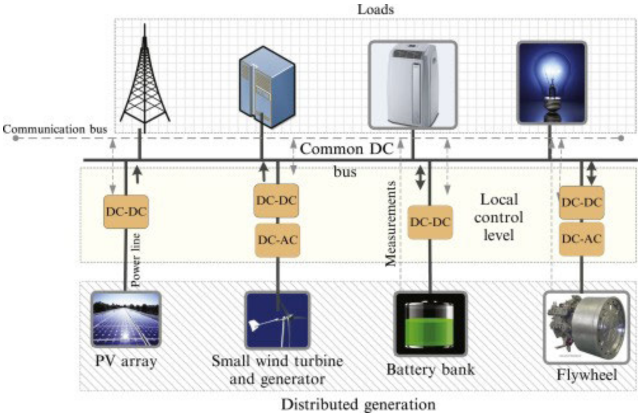


**FIGURE 11.** Microgrid system [128].

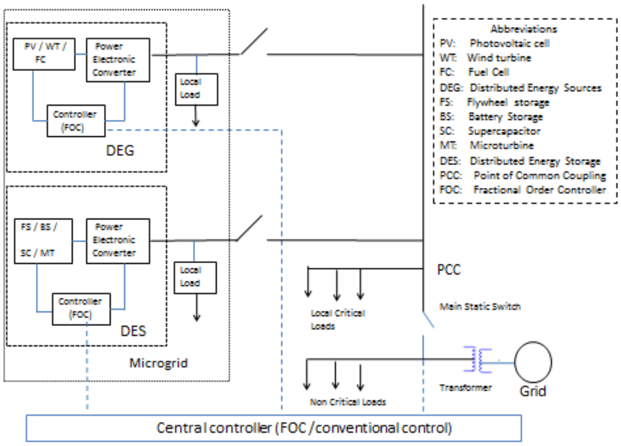


**FIGURE 12.** A typical microgrid system with fractional order control.

event of a power outage or non-functioning of the main grid due to repair or maintenance. A microgrid can be powered by distributed generators (DG), batteries, and/or renewable resources like solar panels, fuel cells and wind turbines [126]. It is connected to the main grid at a point of common coupling (PCC). A switch can separate the microgrid from the main grid automatically or manually, and it then functions as an islanded microgrid, in the event of a fault in the grid or power shortage [127].

Power electronic converters provide cost-effective and flexible interfaces between the distributed energy sources and the network. They also allow the efficient control and management of the power flow with the development of advanced control strategies. Microgrids can be DC microgrids, AC microgrids or hybrid DC and AC microgrids according to the method of transmission and distribution of power. A review of the use and control of power electronic converters in microgrids can be found in Xiongfei *et al.* [129]. As a microgrid system has many energy sources, power-sharing between the different DG units and energy management strategy becomes very crucial. A typical microgrid system with controller is shown in Figure 12. This section focuses on the application of fractional control in smart grids and microgrids.

### 1) FRACTIONAL-ORDER CONTROL IN SMART GRIDS

The authors in [130] designed a fractional order Smart Grid system to account for the non-linearities in the system caused by chaotic oscillations due to inverter current and initial conditions. The smart grid dynamics were analyzed by making the rotation angle, load voltage and angle, and angular velocity parameters constant and the inverter current variable. Bifurcation analysis showed the existence of the largest positive Lyapunov coefficient in fractional order. A fractional order model of the system was derived and the Lyapunov stability was investigated. They designed a FO adaptive sliding mode controller and GA-optimized FOPID controller to control the chaotic oscillations. The GA based method was found to be more efficient and this was implemented on FPGA to show that the system could be realized on hardware.

A Fractional order PID controller for Load Frequency control was proposed by the authors in a power system integrated with renewable energy sources and electric vehicles [131]. In large grid systems with many interconnected control units, Load frequency control is required to maintain the active power generation and demand requirement according to the loads and for proper frequency control. Frequency deviations caused by fluctuations in load or irregularities in the renewable energy sources have to be taken care of by the controller. The tuning was done by several evolutionary algorithms such as Imperialist competitive algorithm (ICA), differential algorithm (DE), etc. The fractional parameters give more flexibility and accuracy to the design of LFC. The use of EVs providing secondary reserve was also investigated and the frequency deviation was found to be much lesser in the areas using EVs. The robustness of the proposed controllers was simulated with -20% and 20% change in the time constants of the governor and turbines. The frequency deviation and settling time were also not affected by changes in the tie-line synchronization coefficients.

The elimination of harmonics is a critical problem in power systems when non-linear loads are connected to the grid. This leads to poor input power factor and degradation of power quality. Passive filters may cause resonance in supply and load and hence, shunt active power filters (SAPF) can be used to mitigate the harmonics and to improve reactive power. The paper [132] describes an FO-Integral plus Proportional controller (FOIP) for Direct Power control (DPC) of SAPF. The SAPF is a three-phase Voltage Source Inverter, which has a DC side capacitance and AC side inductances. The DPC method controls the active and reactive power using two hysteresis controllers. The proposed method used the FO-DPC algorithm and the FO-IP controller is used to generate the active power reference and regulate the capacitor voltage by comparing it with the DC reference voltage. The system was experimentally verified in the dSPACE 1104 board with

MATLAB real-time environment with both PI and FO-IP controllers. The robustness of the system was verified by introducing non-linear load variations, change in reference voltage and by turning on the SAPF. It was seen that the FO-IP controller reached the reference voltage faster with a lesser value of alpha and overshoot was eliminated. The THD was reduced to 2.4% with the FO-IP controller compared to 5% with the PI controller. The FO controller showed better dynamic and steady-state responses and gave lower settling time and harmonic distortion. This is a low-cost solution and can be integrated into inverters used in renewable energy applications.

Hybrid renewable energy systems use multiple energy resources like wind and solar, which can be integrated to the grid to provide power to consumers. The challenge is to ensure a continuous and stable power supply to the consumers according to the variable load demands from the non-continuous supply provided by the resources. A FO PI/PID controller was implemented in [133] for a smart residential building integrated with a hybrid renewable system using solar panels and wind turbines, designed to give a voltage of 690V DC, greater than the 670V DC from the grid. This was converted to 220V AC for the residential homes by a 3 phase inverter. The controller acted on the DC link voltage and generated references in synchronous frames according to the error. PI, PID, FOPI, FOPID controllers were tested for comparison. The inverter with the filter formed the plant and the controllers were designed according to frequency response specifications and tuned by analyzing the Bode plots of the dynamic system. The system was simulated for a residential building using the wind-solar data profile obtained from the Capo Vado site reports. It was observed that the FO controllers could control the periodic variation of the system much better. The robustness of these controllers to uncertainties was seen by the flat phase around the cross-over frequency. This feature makes it more flexible to design the parameters. Lesser THD, overshoot, lesser settling time were obtained with FO controllers. FOPID controller had the least overshoot and FOPI had a lesser overshoot than PI.

### 2) FRACTIONAL-ORDER SLIDING MODE CONTROL IN MICROGRIDS

A fractional order Terminal Sliding Mode Controller (TSMC) was proposed by NasimUllah *et al.* for a DC-DC boost converter connected to a constant power load in DC microgrid and compared with integer order controller [134]. The system under consideration had a source side boost converter that regulated the DC link voltage and a load side converter feeding a tightly regulated resistive load. The load side converter acted as a constant power load for the boost converter with a negative impedance characteristic. This made the source side boost converter susceptible to instabilities. The mathematical conditions for stability were stated and convergence conditions proved. Numerical simulations showed that the FO controller had better tracking and smoother inductor current for constant instantaneous power load and known variations. For load changes by 10 % and known parameters, the FOTMSC showed faster convergence, lesser tracking error and lesser oscillations. Overshoot was considerably reduced and it showed better robustness and less chattering compared to the IOTSMC. It also showed better performance in the case of source and load variations and parameter uncertainties.

A hybrid renewable energy source (HRES) system connected to grid/microgrid for a three-phase load was developed by Sedhaghati. R and Shakarami MR with an adaptive fractional fuzzy sliding mode strategy for control and energy management [135]. The HRES had a PV panel as the primary power source, with a fuel cell (FC) as the secondary resource and supercapacitor (SC) and battery banks for energy storage. The SMC ensured system stability and the fuzzy controller approximated the dynamics for faster convergence. Fractional control achieved an extra degree of freedom and hence allowed access to more parameters. The PV unit was connected to the DC-link capacitor through a boost converter controlled by MPPT. The battery bank charges the SC and provides backup. The SC and battery devices were controlled with a buck-boost converter. The FC unit was used to charge the battery up to its maximum. All the units were connected in parallel to the grid through a voltage source inverter which is controlled by the proposed controller. The system state equations were written and the sliding surface with fractional order was expressed as: $S = -\lambda_1 e - \lambda_2 \int e - \lambda_3 D^{\alpha-1} e$, where $e = x_d - x$ is the tracking error, $x = [P\,Q]^T$ where $P$ and $Q$ are the real and reactive powers at the PCC bus. The control signal was obtained by differentiating S and equating $\dot{S} = 0$. Adaptive fuzzy control was used to obtain the uncertain parameters in the fractional SMC and to ensure that the signal could be tracked with precision.

Delghavi *et al.* proposed a FOSM voltage control strategy for the islanded operation of distributed energy resources for off-grid electrification [136]. The efficiency of the proposed controller was proved with time-domain simulations, and showed that the AC output voltage quality was maintained even for unbalanced load currents and was robust to load switching variations.

### 3) FRACTIONAL-ORDER PID CONTROL IN AC/DC MICROGRIDS

A Kriging based surrogate modeling optimization strategy was discussed for the design of FOPID controllers for a microgrid system by I. Pan and S. Das in their paper [137]. Kriging models are good for accurate approximations of linear and non-linear trends by using different spacial correlation functions and takes lesser time for optimization. The microgrid had different alternative power resources like a wind turbine, PV cell, Fuel cell and diesel generators, and battery and a flywheel system for energy storage. The FOPID controller was used to minimize the frequency fluctuations and deliver good power quality. The frequency deviation signal was passed through the Oustaloup filter to generate the approximated fractional operator, which combined with the gains of PID gave the proposed FOPID controller. The controller was used to regulate the power delivered by the fuel cell and Diesel energy generator (DEG), whereas the flywheel and battery unit parameters were taken from the grid frequency.

A plug-in type fuzzy fractional-order PID controller was used by M.Moafi *et al.* for the energy management of a microgrid with a wind turbine, microturbine and energy storage [138]. The performance of the controller in both grid-connected and islanded modes were tested. The DG units were connected to the grid at the PCC through a static switch and could be operated in grid connected mode with the switch closed and islanded modes with the switch open. A master DG unit could control the operations in islanded mode, with the other resources as slaves. The particle swarm optimization technique is used to minimize the IAE and ISE criteria and obtain the parameters of the FOPID. In the islanded mode, as the power flow to the microgrid is interrupted, the FFOPID controls the energy storage units to inject active power into the system. Simulation results showed that the power available and efficiency was increased using the proposed controller. Increased frequency stability, fast response and lesser overshoot were the advantages of the proposed scheme.

A multi-objective population-based external optimization(MOPEO) method for FOPID controller was designed for the operation of an islanded microgrid integrated with solar and wind power, fuel cells, diesel energy generator and flywheel and battery energy storage systems [139]. The system was simulated and the frequency deviation, control output and deficit power deviation were obtained and a comparison was done between MOPEO and NSGA-II optimized PID/FOPID controllers. The proposed method with FOPID was more robust and gave better results.

## D. ELECTRIC AND HYBRID VEHICLES

Electric vehicles (EV) are increasingly becoming popular due to the increasing concerns of environmental pollution. EVs have much higher efficiency and require lower maintenance compared to fuel-based cars, in addition to providing relatively pollution-free energy. EVs are completely run on electricity, whereas HEVs have two sources of power, an Internal Combustion Engine (ICE), and an energy storage system/battery [140] (see Fig. 13). Power electronic interfaces are an integral part of such vehicles. The main parts of an electric vehicle are the electric motor, inverter to control the traction motors, power drive train which also provides regenerative braking, batteries, charger and the control system [141]. The power trains can be different according to the type of EV, but essentially have a Power factor Correction control, traction inverter and DC-DC Auxiliary power module for converting voltages into suitable lower voltages [142].

All these systems require robust controllers since the efficiency is directly affected by the control scheme. The next subsections describe some EV/HEV systems where fractional order controllers have been effectively used.

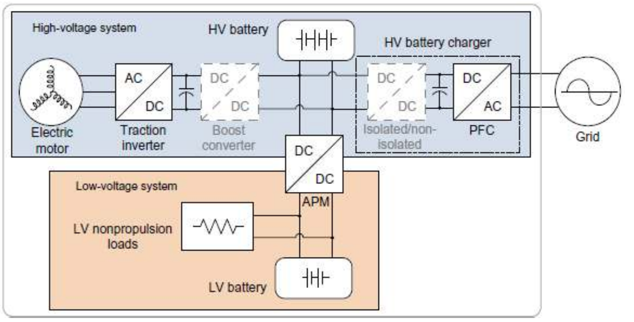


**FIGURE 13.** A typical power train for electric vehicle [142].

### 1) FRACTIONAL ORDER PI/PID CONTROL IN ELECTRIC AND HYBRID VEHICLES

In [143], the authors designed a FOPID controller for the speed control of an EV on concrete roads. The vehicle was modeled as a second-order transfer function taking the parameters of the vehicle, motor and road conditions into consideration. IOPID controllers were designed for the system using classic tuning methods, whereas FOPID controllers were designed using optimization methods as well as Padula Visioli, Ziegler-Nichols (ZN) methods. The overshoot, settling time and performance indices were better for the FOPID controller. A combination of ZN tuning with Active Set (AS) optimization worked best for FOPID design.

A PSO-based FOPID controller was designed for a HEV working in series/parallel split power mode to stabilize it against parameter variations and disturbances [144]. The generator speed could be positive or negative according to which the vehicle operated in series or parallel mode, using a gear system that decoupled the engine speed from wheel speed. The speed of the vehicle varied with time and road slope and had to be controlled accordingly. Simulation of the plant with FOPID and IOPID controller was done with variations in mass, air-friction and drag coefficient, and the performance coefficients of IAE, ISE, ITSE, and transient performance were checked. The FOPID controller gave better performance compared to the IOPID controller.

An FOPID controller was used for a three-level boost DC-DC converter in a hybrid energy storage system of an EV [145]. The currents and voltages had to be adapted between the storage elements and various parts of the EV. The FOPID controller was designed based on the robustness criteria, sensitivity functions and phase margin and optimized using the fmincon solver in MATLAB.

An FOPI controller was designed for the Direct torque control (DTC) for the traction system using an induction motor of an EV [146]. The modeling of the batteries, power electronic converters, traction and control system was done based on the speed and mass requirements. DTC controlled the torque and flux independently by selecting the inverter switching states for driving the motor. The system was simulated with step and ramp inputs and the ITAE was evaluated. Another test was done to obtain the speed profiles according to the

**TABLE 4.** Fractional order control in smart grids, microgrids and electric vehicles.

| Type of Fractional controller | Optimization/Analytical method | Remarks | Reference |
|---|---|---|---|
| **Smart Grids Applications** | | | |
| FO Adaptive SMC, FOPID | GA | Chaos control, Hardware implementation on FPGA | [130] |
| FOPID for Load frequency control | ICA, DE, hGSA-PS | System with renewable energy sources and EV,Simulation | [131] |
| FO-Integral plus Proportional controller | Analytical frequency domain design method | Direct Power control (DPC) of SAPF, Implementation in dSPACE | [132] |
| FO PI/PID controller | Analytical method | Simulation of SG integrated with a HRES in smart residential building | [133] |
| **Microgrid Application** | | | |
| FO Terminal SMC | Analytical method | Control of boost converter with constant power load in a DC microgrid | [134] |
| FO SMC | Voltage control strategy | Islanded DER system with constant power load | [136] |
| Fractional Fuzzy SMC | Adaptive fuzzy strategy | Grid connected microgrid with HRES system and a 3-phase load | [135] |
| FOPID | Kriging based optimization | Microgrid frequency control,comparison with IO controllers | [137] |
| Fuzzy FOPID | PSO algorithm | Islanded and grid-connected operation | [138] |
| FOPID | Multi-objective External optimization method | Frequency control of islanded Microgrid and comparison with NSGA-II,Kriging methods | [139] |
| **Electric vehicles Applications** | | | |
| FOPID control | Analog tuning with active set (AS) optimization | Speed control of Electric vehicles on concrete roads | [143] |
| FOPID control | PSO method | Hybrid vehicles in split power mode | [144] |
| FOPID control | fmincon solver | Control of a boost converter in EV | [145] |
| FOPI | Analytical method | Direct Torque control of traction system of an EV | [146] |
| FOPI | Analytical method | Stabilization of EV battery with microgrid with islanded and grid connected modes | [147] |
| Fuzzy FOPD /FOPI | GA | Speed control of a Hybrid vehicle with electronic throttle control | [148] |
| PD and FOPI, | fmincon | Adaptive Cruise control in EV | [149] |
| Fractional adaptation strategy | FO Model reference adaptive controller | Cruise control in Electric vehicle | |

New Europe Drive Cycle (NEDC), which is developed to test models according to climatic conditions, traffic, geographical conditions etc. It was seen that the FO-PI controller showed improved system performance.

A FOPI controller was designed for a microgrid for the smooth transition between the islanded and grid-connected modes [147]. The storage system had two EV batteries, a DC-DC converter and DC-AC inverter, both of which can operate on grid-connected and islanded modes. In grid-connected mode, the two batteries give constant P/Q and controlled by the DC-DC converter, while the inverter supports DC bus voltage. The DC bus voltage is stabilized by the DC-DC converter and V/f strategy used by the inverter in islanded mode. The controller gave a better phase margin and reduced bandwidth and lesser resonance peak.

A fuzzy FO strategy was used for the speed control of an HEV with electronic-based throttle control [148]. Fuzzy FOPD / FOPI controllers were used as primary controller and secondary controller respectively in the cascade control loop. Tuning of the controllers was done using Genetic Algorithm optimization. Simulation on LABVIEW was carried out and performance was compared with IOPD, IOPI, FOPD and FOPI controllers. It was seen that the proposed fuzzy FOPD / FOPI controllers outperformed the other controllers.

### 2) FRACTIONAL-ORDER CRUISE CONTROL OF EV

A fractional hybrid control strategy was used for Cruise Control (CC) and adaptive cruise control (ACC) at low speeds considering a hybrid model of an electric vehicle [149]. Two fractional order PI controllers were designed for throttle control during acceleration and brake control during the deceleration in CC mode. ACC mode was tried with two vehicles, one working as the leader and the other, automatic, with the distance between them being adjusted by a PD controller, and the FO controller used for speed control. The inter-distance error is negligible in the proposed controller when compared with integer PI controller.

The authors in [22] designed a fractional order model reference adaptive controller (FOMRAC) for cruise control of an EV. The power train with the motors, transmission system, controller, battery management system, power converters and cruise control system was modeled and simulated. In MRAC, a reference model is chosen to get the required performance. The inner current loop and outer cruise control loop are controlled by the FOMRAC, which is tuned using a fractional adaptation law. Simulation results show the effectiveness of the proposed scheme. Table 4 summarizes different fractional-order schemes for smart grids, microgrids and electric vehicles.

## VI. ADVANTAGES AND LIMITATIONS OF FRACTIONAL ORDER CONTROLLERS

This section discusses the advantages and disadvantages of typical fractional order controllers used in power electronic applications.

### A. ADVANTAGES OF FOPI/FOPID CONTROLLERS

FOPID controllers in electrical drives were found to give smoother control signal with lesser control effort. This is due to the use of the fractional order integrator and differentiator, which uses past values with decreasing weights (long memory effect) and hence give a better filtering action [79]. Also, the current and power consumption for FOPID was found to be lesser when compared to the IO controllers. This leads to more energy-efficient systems. The number of switchings and hence switching losses were found to be reduced by using FOPID control, thus again decreasing the control effort, and increasing the life of the switching devices [63]. This is a very desirable performance, as it can decrease the transient disturbances and EMI due to the switching. Such energy-efficient systems lead to a greener environment, which is the need of the hour.

The same FOPID controller parameters can be used without retuning on different plants with the same ratings, but varying parameters, i.e., they are robust to parameter variations. FO controllers have flat phases and hence a constant phase margin at the gain cross over frequency due to fractional elements, resulting in isodamping, providing robustness over a wide range of gains. IO controllers require very high order integer order transfer functions to achieve the same properties.

Chaotic behaviour is rejected in converters such as boost converter. In the control of wind turbine generators, the FOPI controller was able to track input command despite the backlash phenomenon, whereas the IO controller becomes unstable. Also, FOPI/PID controllers incorporated with fuzzy control scheme gave sinusoidal grid currents, with reduced THD at unity power factor [113].

In PV systems, the varying irradiance levels and environmental conditions have been tracked efficiently for MPPT by FOPID controllers. They have been efficiently used in MPPT control of DC-DC converters and gave better performance indices with lesser overshoot. FOPID controllers used for PV grid-connected systems gave lesser values of THD under varying solar irradiations. FOPID controllers incorporated with the passive (PFOPID) and perturbation schemes (PoFOPID) showed remarkable improvement in control effort in temperature variation and the DC-link tracking performance [104], [106]. FOPI/FOPID control has also been incorporated in the control of electric and hybrid vehicles with better transient response performance than PID controllers, and are effective in cruise control also due to their easy adaptation to uncertainties. The FOPI/FOPID controllers reported in the literature for various applications exhibited improved dynamic response, lesser steady state error, lesser overshoot and settling time.

### B. ADVANTAGES OF FOSMC

SMC is a robust control technique that is used extensively for the control of non-linear and time-varying systems, such as power electronic converters. FO Sliding mode controllers, being extensions of the conventional SMC, are more robust than SMC. These are best suited for the control of non-linear systems with parameter variations and disturbances, or chaotic systems, such as the boost converter. It is seen that chattering and oscillations are completely removed.

FO SMC was used for the chaotic fractional order system Lu used in power distribution [150]. The sliding surface converged to zero very fast, saving energy, reducing device deterioration and had a high speed of control. A FOSMC designed for a Maglev system showed better disturbance rejection, lesser control effort, faster convergence of error trajectory to the sliding surface, compared to SMC [151].

Sliding mode control is very popular in the control of wind energy conversion systems, due to its robustness and ease of implementation, but still suffer from chattering and oscillations. FOSMC reduces the chattering phenomena, as here the error variables follow the FO sliding surface and still reach the origin, and hence the switching devices do not need to switch frequently [114]. This prevents the deterioration of the switching devices due to frequent switching and conserves energy. Active and reactive power regulation of the converters controlled with FOSMC in PMSG and DFIG was found to be better than the conventional controllers. The integration of wind energy systems into existing power systems may affect the stability of the system. Power quality should be maintained, with less injection of harmonics into the grid. For such systems, FOSMC seems to be a good option and has been found to reduce THD. FOSMC schemes have also been found to reduce subsynchronous control interference in wind farms [121], [123].

Improved versions of FOSMC such as FO Terminal SMC assures the convergence of error to equilibrium in a finite time and gives faster response to load variations [70]. FOTSMC was also used to overcome the destabilization problem in power converters with constant power load in microgrids [134]. Better power balance and load sharing is observed for hybrid renewable energy system in microgrids using a fractional adaptive fuzzy strategy.

### C. LIMITATIONS OF FO CONTROL

1) With all the advantages of flexibility in control, the adoption of Fractional-order controllers by the industry is still a major concern, due to the issues of complexity and cost of implementation. As of now, the fractional orders are approximated by using higher integer-order transfer functions, which increases the

computational resources and cost. This gives rise to the obvious question of the need for fractional-order if it is finally implemented by integer-order. Also, this gives rise to more tuning knobs for adjustment of the parameters of approximation. The approximated transfer functions, apart from being of higher order, may not be understood properly by many control engineers.

2) For digital implementation, digital devices such as PLC, FPGA etc. are used for discrete approximation methods. These devices require large memory, and larger sampling periods than the computation length time [41].
3) Further research may be required to specify simpler parameter tuning knobs for FO controllers to be accepted by the industry.
4) The use of optimization techniques has reduced the complexity of the design of fractional controllers. But the advantages are limited if the design specifications are lesser in number than the number of controller parameters. Heuristic optimization algorithms can be used for multi-objective optimization for tuning, but the random search nature of such algorithms require statistical analysis( such as mean and standard deviation) and multiple runs for a reliable solution. Cost functions also need to be carefully chosen to give the best results.
5) Even though research is ongoing for the realization of fractional components using mixed-mode design, this has to be available as a cost-effective solution that can be implemented on programmable control cards.
6) Further research may be required to specify simpler parameter tuning knobs for FO controllers to be accepted in the industry. Many software tools have been developed for FO implementation, which can be used with computer-aided design modules. But the users may not necessarily be familiar with these tools and unless these modules integrated with control cards are available as low-cost replacements for IO controllers, it is difficult to be accepted by the industry.
7) At present, HIL realizations for fractional controllers are expensive, and limits the research on FO controllers to simulations. Also, the operating frequency of less sophisticated controllers may limit the switching frequency and sampling time, unless advanced controllers are used. The HIL platforms may give varied results from simulation because of their time delay and sudden disturbances.
8) In some cases, the improvement in the dynamic characteristics compared to the IO controllers may not be good enough if the complexity and cost of implementation are much more.
9) FO sliding mode strategies may be more useful for complex systems with high non-linearities than FOPID controllers. However, for simpler systems, it may be more cost-effective to work with FOPID controllers or IO controllers with good optimization techniques.
10) The efficiency of FO SMC schemes depend on the proper choice of the sliding surface and control laws.

## VII. DISCUSSION

The Fractional-order controllers have several technical advantages over integer-order controllers. But for wide acceptance of these controllers in the industry, the limitations as discussed in the above section have to be overcome. The use of FO controllers should be properly justified by superior performance or at least the same efficiency as the conventional controllers. A Technology Readiness Level(TRL) may have to be established for an industry-implementation ready FO controller [152].

The variation of controller parameters may sometimes result in instability, and hence the sensitivity of the controller to variations in the controller parameters should be studied. It would be easier for an operator without the knowledge of fractional calculus to control the system, if provided with a set of tuning rules and instructions to modify the controller parameters. A fragility index of the fractional controller may hence be required for the effective implementation of such controllers in the industry [152], [153].

Most of the fractional orders are approximated by using higher integer-order transfer functions, which increases the computational resources and cost. This could be rectified by using the analog realization of FO controllers as discussed in Section II(D). Analog fractional order elements can be obtained by using interconnected active and passive elements or as single component fractors manufactured using the fractional property of different materials. These can be easily implemented in integrated circuits to obtain fractional order systems. It should be possible to change the orders in analog IC designs for fractional order elements. This has the advantage of a low-cost solution because of mass production benefits. The realization of low-cost FO control units with IDE will be an attractive solution for industry acceptance of FO controllers. Ongoing research in the materials field may give rise to low-cost fractional order elements in the future [152].

The use of metaheuristic optimization techniques has reduced the complexity of the design of fractional controllers. With the advances in artificial intelligence and fuzzy logic, better optimization techniques can be used to tune the FO controllers. Such methods, with the inherent robustness of the FO controllers, can be used to obtain the desired system response.

FOPID controllers are the extensions of the integer order PID controllers, which are the dominant controllers used by the industry. Hence it can be expected that it will be easier to incorporate FOPID controllers soon in the industry, with some of the solutions as proposed in [152]. An already existing PID controlled system for a DC motor was converted into an FOPID system by incorporating an additional loop to the system [154]. This incorporated fractional dynamics into the existing system without internal changes to the original system. Such systems will be very useful in modifying the existing PID controllers. A retuning mechanism was defined taking into account the system specifications. Another research paper proposed a simpler tuning method for FOPID using the coincident zero method. Here, a set of only 3 tuning parameters were required for tuning instead of five. In this method, the values of the integer and differential order were chosen to be the same ($\lambda = \mu$), so that good relative stability is obtained for both low and high frequencies.

Such methods can help in the acceptance of FO controllers into the industry. Other fractional order controllers such as the TID controllers are also being used in power systems for load frequency control and gives better results in comparison to the IO PI, I and PID controllers [155], [156]. A third-generation CRONE controller was reported in the literature for the robust control of a wind turbine [157]. Many such fractional-order strategies are under research due to the many advantages of such controllers over IO controllers.

## VIII. CONCLUSION & FUTURE TRENDS

### *A. CONCLUSION*

Industry 4.0 dictates more intelligent controllers with enhanced connectivity and good dynamic performance. This paper attempts to review and highlight the advantages of the various fractional control strategies in power electronics. Control of power electronic systems is complicated due to their inherent non-linearities and hence require efficient controllers. The energy requirements of the future demand the increased use of renewable energy sources which require power converters for conditioning and control. Fractional-order controllers have very robust performance, and when combined with certain functionalities may become the power controllers of the future.

A brief introduction to the definitions of fractional calculus and types of fractional order control along with software tools for implementation are discussed. Developments in the analog IC implementations of various fractional order elements can be used to realize various fractional order controllers at lower costs. The extra parameters of the fractional controllers give them more flexibility and the ability to meet more specifications. The fractional PI/PID controller, fractional sliding mode controller and fractional repetitive controller etc. have been discussed for various stand-alone power converters.

FO control in electric drives has been shown to give better speed tracking and better Gain and Phase Margin in various studies. The application of fractional order control in renewable energy applications like solar and wind energy conversion systems showed a fast dynamic response and tracking accuracy under varying climatic conditions. In hybrid systems connected to smart grids/microgrids, it was seen that FO control allowed the injection of an almost proper sinusoidal current into the grid, reduced THD and gave increased frequency stability. FO control in electric and hybrid vehicles showed better dynamic response and robustness to parameter variations. Analog and digital implementations of these systems are possible, and experimentation with Hardware-in-loop platforms verifies simulated results.

Results obtained from recent research papers show that the transient response specifications of overshoot, settling time etc. have been met with lesser control effort and better error performance indices by fractional controllers. One of the main advantages of the fractional order controller is the robustness for a wide range of gains. The robustness of fractional order controllers against parameter variations makes them an excellent choice for power electronic converters, which are difficult to control. The use of multi-objective optimization techniques makes the tuning of the fractional order parameters easier. The development of various approximation techniques and dedicated software tools for fractional control has reduced the complexity introduced due to the extra parameters. The combination of fuzzy logic and artificial neural networks with fractional control can be used to improve the efficiency of FOC. The current research shows that more energy-efficient and greener solutions can be provided by using fractional-order controllers in highly nonlinear power electronic applications.

### *B. FUTURE TRENDS*

Plug-in type fractional order controllers with inbuilt functionalities maybe developed for industrial applications which are currently still dominated by linear PID controllers. Extensions of fractional order calculus like variable and complex order calculus can be explored for power converter control. There is tremendous scope for the design of modular fractional order intelligent controllers which can be embedded into power converters for the development of the smarter power electronic systems of the future.

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