A control approach for the operation of DG units under variations of interfacing impedance in grid-connected mode

S. Kazem Hoseini[a], Edris Pouresmaeil[b,c,1], S. Hassan Hosseinnia[d], João P. S. Catalão[c,e]

[a] Faculty of Electrical and Computer Engineering, Babol (Noshirvani) University of Technology, P.O. Box 47135-484, Babol 47144, Iran, Email: k.hoseini@stu.nit.ac.ir
[b] Centre for Energy Informatics, Faculty of Engineering, University of Southern Denmark (SDU), Odense, Denmark, Email: edp@mmmi.sdu.dk
[c] INESC-ID R&D Unit, Inst. Super. Tecn., University of Lisbon, Lisbon, Portugal, Email: catalao@ieee.org
[d] Department of Precision and Micro System Engineering, Delft University of Technology, The Netherlands Email: s.h.hosseinniakani@tudelft.nl
[e] University of Beira Interior, Covilha, Portugal, Email: catalao@ubi.pt

Abstract-Voltage source converter (VSC) can be considered as the heart of interfacing system for the integration of distributed generation (DG) sources into the power grid. Several control methods have been proposed for integration of DG sources into the power grid, and injection of high quality power. However, the converter-based DG interface is subjected to the unexpected uncertainties, which highly influence performance of control loop of DG unit and operation of interfaced converter. The interfacing impedance seen by interfaced VSC may considerably vary in power grid, and the stability of interfaced converter is highly sensitive to the impacts of this impedance changes; then, DG unit cannot inject appropriate currents. To deal with the instability problem, a control method based on fractional order active sliding mode is proposed in this paper, which is less sensitive to variations of interfacing impedance. A fractional sliding surface, which demonstrates the desired dynamics of system is developed and then, the controller is designed in two phases as sliding and reaching phases to keep the control loop stable. Stability issues of the control method are discussed in details and the conditions in which the proposed model works in a stable operating mode is defined. The proposed control method takes a role to provide high quality power injection and ensures precise references tracking and fast response despite such uncertainties. Theoretical analyses and simulation results are established to confirm the performance and feasibility of the proposed control method in DG technology.

Keywords- Voltage Source Converter; Distributed Generation; Interfacing Impedance; Fractional Order Control; Active Sliding Mode Control.

I. Nomenclature

A. Indices

x and y	a, b, c
z	d, q

B. Abbreviations

VSC	Voltage Source Converter
DG	Distributed Generation
FOC	Fractional Order Control

[1] Corresponding Author: Edris Pouresmaeil, Email: edp@mmmi.sdu.dk, Tel: +45-40120982

ASMC	Active Sliding Mode Control
F_rASMC	Fractional Order Active Sliding Mode Controller
THD	Total Harmonic Distortion
SVM	Space Vector Modulation
PID	proportional-Integral-Derivative
PF	Power Factor

C. Variables

v_{xN}	Leg voltages of VSC
v_{xo}	Phase voltages of VSC
D_{xN} and D_{yN}	Switching variables of each leg of VSC
i_x	Converter output currents
v_{gx}	Utility grid voltages
v_{dc}	DC-link voltage
i_{dc}	Input DC current
U_x	Switching state function
i_{dref}	d-component of reference current
i_{qref}	q-component of reference current
P	Active power
Q	Reactive power
a and t	Limits of the fractional operation
h	Order of the fractional operation
A, B and T	System matrices
r	Lump of uncertainties
x	System state
S	Fractional sliding surface
e	Dynamic errors

D. Parameters

R	Equivalent interfacing resistance seen by the VSC
L	Equivalent interfacing inductance seen by the VSC
C	DC-link capacitor
ω	Angular speed of synchronous reference-frame
${}_aD_t^h$	Fractional order operator
Γ	Gamma function

δ	Specified positive constant
k_p, k_i, and λ	Design parameters of fractional order PI control
γ	Switching factor of sliding mode control
β	Positive constant

II. Introduction

Distributed Generation (DG) technology based on renewable energy sources is getting more attentions from electrical engineers and scientists, which consider different goals such as environmental, economical, and technical viewpoints [1]. Furthermore, DG technology can offer higher power quality or reliability to the loads and grid, produce electricity at a site closer to customers, and reduce stress of utility grid during peak of demand from the load side [2].

Renewable energy sources are more preferable option for empowering the DG units near the main grid; since, energy storage is not very satisfying at present and saving energy is a problematic issue. Development of semiconductor switching devices led to high-speed operation of voltage source converters (VSCs), which are capable of delivering high quality power to the loads and grid. Generally, power electronic VSCs are feasible solution to integrate DG sources to the grid due to introduction of real-time controller [3].

Stable operation of control loop in DG unit is an important aspect; so as, an instable control loop cannot inject desired power from DG source to the grid. The interfacing impedance seen by the VSC may noticeably change depending on the configuration of the utility grid (as DG units are commonly installed in weak grids), output filter design, and grid synchronization techniques. Also some phenomena such as cable overload, temperature effect, and saturation often further aggravate the problem. Uncertainties in the impedance seen by the VSC leads to instability in the control of DG interfacing system since the stability is so sensitive to the interfacing impedance variations. As a result of instable controller, the DG system cannot inject the expected currents or persistent oscillations may exist in the injected currents [4]. Hence, it seems crucial to design a control structure for the DG system, which is insensitive to the variations of interfacing impedance.

Several control methods and studies have been reported for integration of DG sources into the power grid such as [5]-[10]; however, a few works have addressed instability problems of interfaced converters in DG technology. Influence of grid impedance on current control loop have been investigated in [11] and a control technique based on adjusting the controller gain was proposed to stabilize interfaced VSC; however, it needs problematic online measurement of interfacing impedance; moreover, changing controller gain may deteriorate other capabilities such as disturbance rejection. An adaptive grid-voltage sensorless control method has been presented in [12] for converter-based DG units, which needs an additional interfacing parameter estimator in a parallel structure to deal with the stability problem. Reference [13] proposed a model reference adaptive control to connect DG units to utility grid through a LCL filter; nevertheless, it uses converter output current as the feedback signal to the controller, which may result in the resonance of the grid current due to the interaction of converter output harmonic current and the resonant circuit formed by the grid inductor and filter capacitor. An impedance-based stability criterion has been verified in [14], which discusses the condition in which a grid-connected converter is stable but it does not present a proper control solution for the instability problem. Effects of grid impedance variations on the stability of the interfaced converter have been investigated in [15]. It has been demonstrated that when either the inductance of the grid increases or the inductance and resistance of the grid increase together, the system stability is adversely affected. Also, [15] proposes an $H\infty$ controller to deal with the instability problem; however, its implementation and obtaining weighting-functions in such systems are very hard.

An effective control method is proposed in this paper, which combines fractional order control (FOC) with an active sliding mode control (ASMC). FOC, which is the use of non-integer order derivatives and integrals, has been realized as an alternative scheme for solving control problems [16, 17]. Applying the notion of fractional order for managing control problem is a step closer to the practical situations since the real world processes are mostly fractional. Some models of fractional order and fractional calculus have been developed to solve different control problems [18, 19]. Sliding mode control is a particular type of variable structure control systems designed to drive and then maintain the system states within a close neighborhood of the decision rule, and is well-known for its robustness to parameter variations and disturbances [20, 21]. Therefore, combining fractional order approaches together with sliding mode control has attracted significant interests [22-26].

The objective of this study is to extend a fractional order active sliding mode controller (F_rASMC) to the current control of a grid-connected three-phase VSC for possessing small steady-state tracking error and fast response of the grid current while maintaining the system insensitive to the interfacing impedance variations. The idea behind this method is that the system states are limited to lie on the fractional sliding surface where the dynamics of the system are only specified by the dynamics of the switching surface. Therefore, the system is invariant in the control design, and the motion of the states trajectory is much less sensitive to disturbances and parameter variations. The control method is easy to implement and it only needs nominal values of the model parameters. Also, it neither affects the capability of disturbance rejection of the current controller nor needs additional estimators.

Further, the stability of the proposed control method has been verified by selecting an appropriate Lyapunov function candidate. Lyapunov theorem is a strong tool to investigate the stability of non-linear control systems [23,27]. In [28], the stability of an extended state observer-based sliding mode control approach for PWM-based DC–DC buck converter systems is analysed using Lyapunov method. This theorem has been incorporated in [29] to prove the stability of a sliding mode controller for a class of unknown nonlinear discrete-time systems. Thus, using this method, the stability of the proposed F_rASMC is analysed and sufficient conditions are derived.

This paper is organized as follows. Following the introduction, a description of the VSC-based DG model is presented in section III. In section IV, basic definitions of the fractional calculus are verified at first and then, design procedure of the proposed control method is given, and the stability issue of the control scheme is discussed. Section V draws simulation results showing a comparison between conventional PI controller and the proposed F_rASMC. Finally, the main conclusions of this paper are illustrated in section VI.

III. VSC-based DG interfacing model structure

This section focuses on a three-phase DG model with a current-controlled VSC. General block diagram of the proposed model is shown in Fig. 1.a. The VSC synthesizes the AC voltage using space vector modulation (SVM) technique with the available DC voltage. Control signals for the SVM are generated from an appropriate controller, and switching pulses are applied to the VSC switches for power injection from DG source into the power grid. To form a grid-connected DG model, the VSC is integrated to the utility grid with an inductive filter and an isolation transformer. The filter is responsible for filtering out the high frequency harmonics generated by VSC switching actions, and the transformer works as an interfacing reactor. Figure 1.b shows the circuit diagram of the grid-connected DG unit with three-phase two-level VSC. The utility grid is modeled as a three-phase AC source with internal impedance using Thevenin's Theorem.

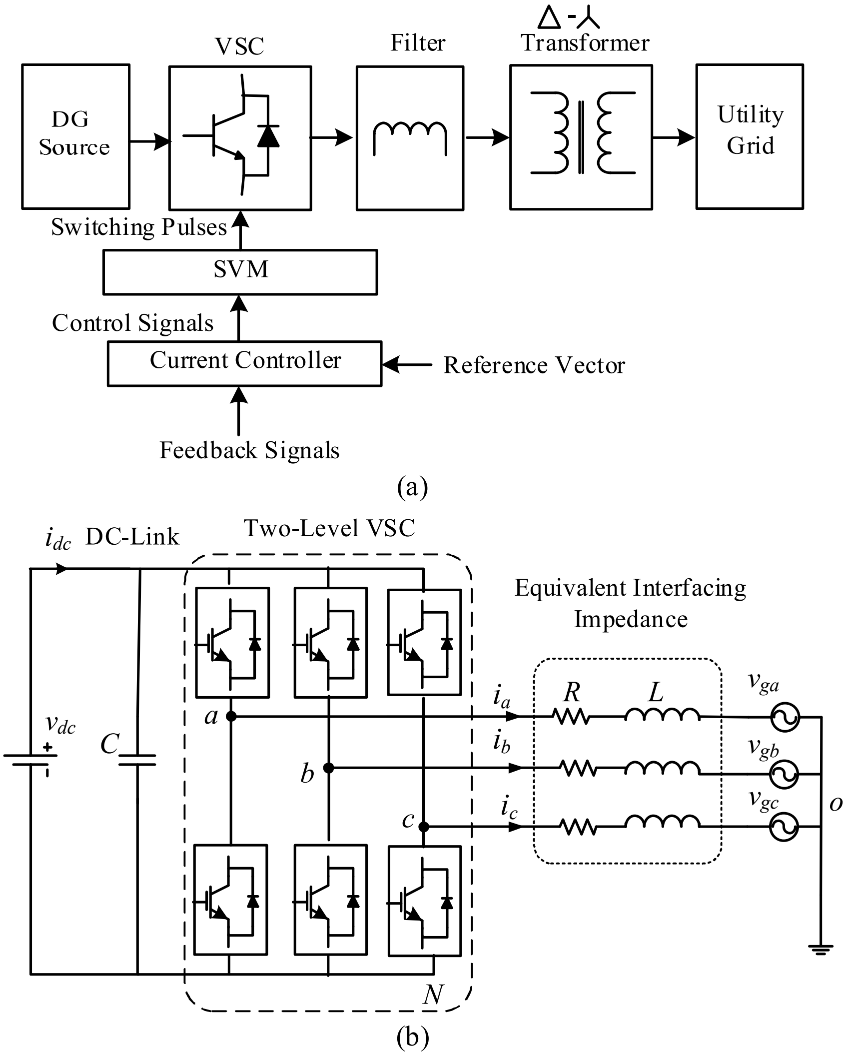

Fig. 1. Generic grid-connected DG unit using three-phase VSC, (a) block diagram of the power system, (b) equivalent circuit diagram with interfaced VSC.

A. Dynamic Analysis of the Proposed Model

To inject high quality power to the utility grid, a current control technique is usually adopted to form the output voltage so that minimum current error is achieved. A VSC controls the magnitude and frequency of the output voltage. The output voltage at each leg of the VSC can be expressed as

$$v_{xN} = D_{xN} \, . \, v_{dc} \tag{1}$$

where, the switching variable D_{xN} determines the switching state of interfaced converter, and can be defined as 1 or 0 when the upper (or lower) switch of the leg is switched ON or OFF. Dynamic equations of the proposed model can be calculated by applying Kirchhoff's voltage and current laws in AC-side and DC-side of the interfaced converter as,

$$L\frac{di_x}{dt} + Ri_x - v_{xo} + v_{gx} = 0 \tag{2}$$

$$i_{dc} = C\frac{dv_{dc}}{dt} + \sum_{x=a}^{b,c}\left(D_{xN} - \frac{1}{3}\sum_{y=a}^{b,c} D_{yN}\right)i_x \tag{3}$$

By defining the switching state function of the VSC as,

$$U_x = \left(D_{xN} - \frac{1}{3}\sum_{x=a}^{b,c} D_{xN}\right) \tag{4}$$

and substituting (4) in (2) and (3), the dynamic equations of the proposed model can be rewritten as,

$$L\frac{di_x}{dt} + Ri_x - U_x v_{dc} + v_{gx} = 0 \tag{5}$$

$$C\frac{dv_{dc}}{dt} + \sum_{x=a}^{b,c}(U_x \, . \, i_x) - i_{dc} = 0 \tag{6}$$

B. *Steady-State Analysis of the Proposed Model and Reference Currents Calculations*

In synchronous reference-frame, a rotating reference-frame is utilized so that all fundamental positive sequence alternating variables become DC quantities in *dq0*-coordinate system; then, objectives of controlling and filtering in the control loop of the system can be achieved easier. By Park transformation matrix, dynamic equations of the proposed model in (5) and (6) can transfer into the synchronous reference-frame with angular speed ω as,

$$L\frac{di_d}{dt} - L\omega i_q + Ri_d - U_d v_{dc} + v_{gd} = 0 \tag{7}$$

$$L\frac{di_q}{dt} + L\omega i_d + Ri_q - U_q v_{dc} + v_{gq} = 0 \tag{8}$$

$$C\frac{dv_{dc}}{dt} + U_d i_d + U_q i_q - i_{dc} = 0. \tag{9}$$

It should be mentioned that zero components of line currents and grid voltages are zero since balanced operation and symmetric abc voltages are considered. Substituting time-varying components by the steady-state quantities and forcing time derivatives to zero, the steady-state expressions of the proposed model in equations (7)-(9) can be calculated as,

$$U_{ds} = \frac{-L\omega i_{qref} + Ri_{dref} + v_{gd}}{V^{*}{}_{dc}} \tag{10}$$

$$U_{qs} = \frac{L\omega i_{dref} + Ri_{qref}}{V^{*}{}_{dc}} \tag{11}$$

$$U_{ds}i_{dref} + U_{qs}i_{qref} - I_{dc} = 0. \tag{12}$$

By substituting the steady-state switching state functions (10) and (11) in (12), the following equation can be obtained

$$\left(i_{dref} + \frac{v_{gd}}{2R}\right)^2 + \left(i_{qref}\right)^2 = \frac{v_{gd}{}^2 + 4RV^{*}{}_{dc}I_{dc}}{4R^2}, \tag{13}$$

which is the mathematical equation of a circle with the center of $\left(-\frac{v_{gd}}{2R}, 0\right)$ and radius of $\sqrt{\frac{v_{gd}{}^2+4RV^{*}{}_{dc}I_{dc}}{4R^2}}$. This circle is shown in Fig. 2 which demonstrates the maximum capacity of interfaced converter for injection of active and reactive power components, i.e. DG can only supply the currents that are inside the circle.

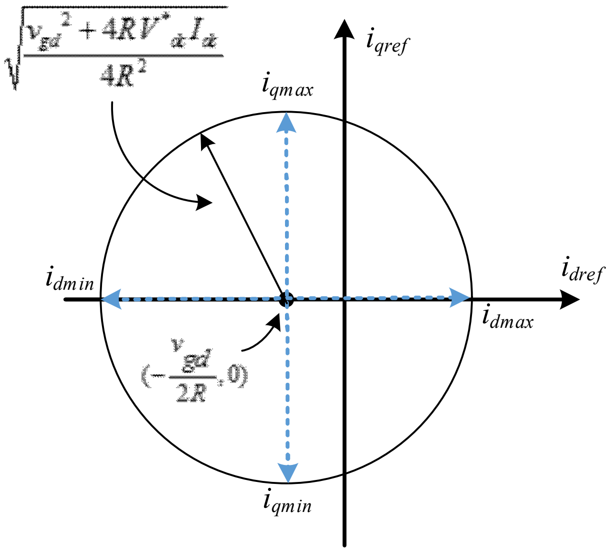

Fig. 2. DG interfacing injection capacity.

Active and reactive power injected from VSC to the grid to control *d*-axis and *q*-axis currents are,

$$P = \frac{3}{2}\left(v_{gd}i_d + v_{gq}i_q\right) \tag{14}$$

$$Q = \frac{3}{2}\left(v_{gq} i_d - v_{gd} i_q\right). \tag{15}$$

Assuming that d-axis of the synchronous reference-frame lies in the direction of grid voltage space vector (d-axis synchronized with the grid voltage space vector), q-component of grid voltage is always zero ($v_{gq} = 0$). Thus, to inject the desired active power P_{ref} to the grid, d-component of the reference current can be obtained from (14)

$$i_{dref} = \frac{2}{3}\frac{P_{ref}}{v_{gd}}. \tag{16}$$

By setting a zero value for the q-component of reference current in the current control loop of DG unit, only active power will be injected by integration of DG sources into the power grid and power factor between the injected current from DG unit and load voltage will be obtained a unity value.

IV. Proposed control design of integrated DG model

The current control structure of a three-phase VSC is the key element in the control design of a converter-based DG system. When the interfacing impedance seen by the VSC becomes highly inductive, the bandwidth of the controller is considerably decreased, which degrades the dynamic performance of the controller [15]. This leads the system to be oscillatory or even unstable. In this section, to deal with the instability problem a F_rASMC is designed for the integration of DG units to the power grid with a three-phase framework. The proposed control scheme has the properties of fast response and small steady-state tracking error of the grid current while keeping the performance of the model insensitive to the interfacing impedance uncertainties. To achieve this goal, a fractional order sliding surface is developed, and then the proposed control method is designed in two stages. The first stage is to choose an appropriate active controller when the system states are supposed to lie on the sliding surface; however, system uncertainties mainly due to the parameter variations may degrade the performance of the active controller, i.e. the states leave the sliding surface. To overcome the problem and adapt the control design to such uncertainties, in the second stage, sliding mode control has been combined with the active controller here, which also has the benefit of handling the drawbacks of discontinuous operating of switching devices. In this technique, the system states are limited to lie on the sliding surface where the dynamics of the system are only specified by the dynamics of the switching surface. Therefore, the system is invariant in the control design, and the motion of the states trajectory is much less sensitive to disturbances and parameter variations.

Basic definitions of fractional calculus are verified first, and design procedure of the F_rASMC, which is a combination of active controller, sliding mode controller and fractional order strategies is given in next step, and finally, the stability issue is discussed for the proposed method.

A. Basic definitions and preliminaries of fractional calculus

Fractional order controllers are the ones with a dynamic characteristic described by differential equations containing derivatives whose order is not an integer number. The fractional operator, denoted by ${}_aD_t^h$, is a compound integration-differentiation operator, which is commonly used in fractional calculus. This operator is a single expression for both the fractional integral and fractional derivative, and can be defined as,

$$
{}_aD_t^h = \begin{cases} \dfrac{d^h}{dt^h}, & h > 0 \\ 1, & h = 0 \\ \displaystyle\int_a^t (d\tau)^{-h}, & h < 0 \end{cases}. \tag{17}
$$

The commonly used definitions in fractional calculus are Grunwald—Letnikov, Riemann-Liouville, and Caputo definitions [30]. The Grunwald-Letnikov fractional derivative definition is given by,

$$
{}_aD_t^h f(t) = \frac{d^h f(t)}{d(t-a)^h} = \lim_{N\to\infty} \left\{ \left(\frac{t-a}{N}\right)^{-h} \sum_{j=0}^{N-1} (-1)^j \binom{h}{j} f\left(t - j\left[\frac{t-a}{N}\right]\right) \right\}. \tag{18}
$$

The second fractional derivative definition, i.e. RiemannLiouville definition, which is the simplest one is defined as follows,

$$
{}_aD_t^h f(t) = \frac{d^h f(t)}{d(t-a)^h} = \frac{1}{\Gamma(n-h)} \frac{d^n}{dt^n} \int_0^t (t-\tau)^{n-h-1} f(\tau) d\tau, \tag{19}
$$

where, Γ is the Gamma function and $n-1 \le h < n$, $n \in N$. The Caputo fractional derivative definition is defined by,

$$
{}_0D_t^h f(t) = \begin{cases} \dfrac{1}{\Gamma(m-h)} \displaystyle\int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{h+1-m}} & m-1 < h < m \\ \dfrac{d^m}{dt^m} f(t) & h = m \end{cases}, \tag{20}
$$

where, $m \in N$ is the first integer number larger than h.

Control techniques which use FOC employ these definitions to apply the idea of fractional integral and fractional derivative in their implementations. In this paper, the third definition, i.e. Caputo fractional derivative definition, is used in the proposed control method.

B. F_rASMC design

The current dynamics of the proposed model in the synchronous reference frame (7) and (8) can be represented by the following state-space equations,

$$
\begin{aligned}
\frac{di_z}{dt} &= Ai_z + BU_z + Tv_{gz} \\
&= (A_o + \Delta A)i_z + (B_0 + \Delta B)U_z + (T_o + \Delta T)v_{gz} \\
&= A_o i_z + B_o U_z + T_o v_{gz} + r,
\end{aligned} \tag{21}
$$

where,

$$i_z = \begin{bmatrix} i_d & i_q \end{bmatrix}^T, \qquad U_z = \begin{bmatrix} U_d & U_q \end{bmatrix}^T, \qquad v_{gz} = \begin{bmatrix} v_{gd} & v_{gq} \end{bmatrix}^T,$$

$$A_o = \begin{bmatrix} -R_o/L_o & \omega \\ -\omega & -R_o/L_o \end{bmatrix}, \; B_o = \begin{bmatrix} 1/L_o & 0 \\ 0 & 1/L_o \end{bmatrix}.v_{dc}, \;\; T_o = \begin{bmatrix} -1/L_o & 0 \\ 0 & -1/L_o \end{bmatrix},$$

and

$$r = \Delta A i_z + \Delta B U_z + \Delta T v_{gz}, \tag{22}$$

where, A, B and T are the system matrices; A_o, B_o, and T_o represent the nominal values of A, B and T; ΔA, ΔB, and ΔT denote the system parameter variations; and r expresses the lump of uncertainties caused by parameter variations, which is assumed to be bounded by δ,

$$|r| < \delta, \tag{23}$$

where, δ is a specified positive constant.

Considering the described model, the errors dynamics can be defined as follows,

$$e = x_{ref} - x = i_{zref} - i_z, \tag{24}$$

where, i_{zref} ($=x_{ref}$) is the reference current. The objective of the F_rASMC is to design the controller U_z such that the model state ($x=i_z$) precisely tracks the reference output current.

Output of the PID controllers is a linear combination of the input, the integral of the input, and the derivative of the input. Fractional order PID controllers are generalizations of PID controllers. Output of the fractional order PID controllers is a linear combination of the input, a fractional integral of the input, and a fractional derivative of the input. The proportional-integral equation, which defines the fractional order PI (F_rPI) [16, 22] control action can be written as,

$$v(t) = k_p e + k_i D^{-\lambda} e. \tag{25}$$

If λ is 1, the result is a usual PI (called as *integer PI*). A switching surface is developed for interfaced converter based on FOC in order to design the F_rASMC. In this sense, a fractional form of the linear compensation PI networks is used to achieve fractional sliding surface of the form PI^{λ}. Based on the generalized (fractional) PI^{λ} structure, a candidate for fractional sliding surface, which represents a dynamic of desired model can be obtained of the form as,

$$S = k_p\left(x_{ref} - x\right) + k_i D^{-\lambda}\left(x_{ref} - x\right); 0 < \lambda < 2, \tag{26}$$

Sliding mode control forces the system state space trajectories to reach the sliding surface in a finite time and to stay on the surface for all future time. The most significant feature of the sliding mode technique is low sensitivity to system parameter variations since the motion in the surface is independent of uncertainties. The main function of the sliding mode controller is to switch between two different structures of the system so that a new type of system motion (sliding mode) exists on the surface. Therefore, the proposed F_rASMC is designed in two phases as, 1- The sliding phase by $S = 0$

2- The reaching phase when $S \neq 0$

In the first phase ($S = 0$), which shows the model operates in desired condition and there are no parameter variations, the active controller can be designed as follows,

$$U_{zeq} = -B_o{}^{-1}(A_o x + T_o v_{gz} + C_0 S), \tag{27}$$

where C_0 is a positive definite matrix for placing poles of the nominal system in its desired values. The active controller works properly when there are no uncertainties; however, the sensitivity of the dominant poles of the current controller is very high to system uncertainties mainly due to parameter variations, which lead to drive harmonic currents through the converter or even the controller may become unstable, i.e. $S \neq 0$. In this phase, in order to drive any states outside the surface to reach the surface in a finite time, a switching control law is developed to construct the F_rASMC as,

$$U_z = U_{zeq} + \gamma sgn(S), \tag{28}$$

where γ is the switching factor, which can be tuned in order to eliminate the effects of parameter variations. As can be seen from (27) and (28), the nominal values of the model parameters are only required to design the controller. The schematic diagram of the proposed control scheme for integration of DG units to the utility grid is illustrated in Fig. 3.a.

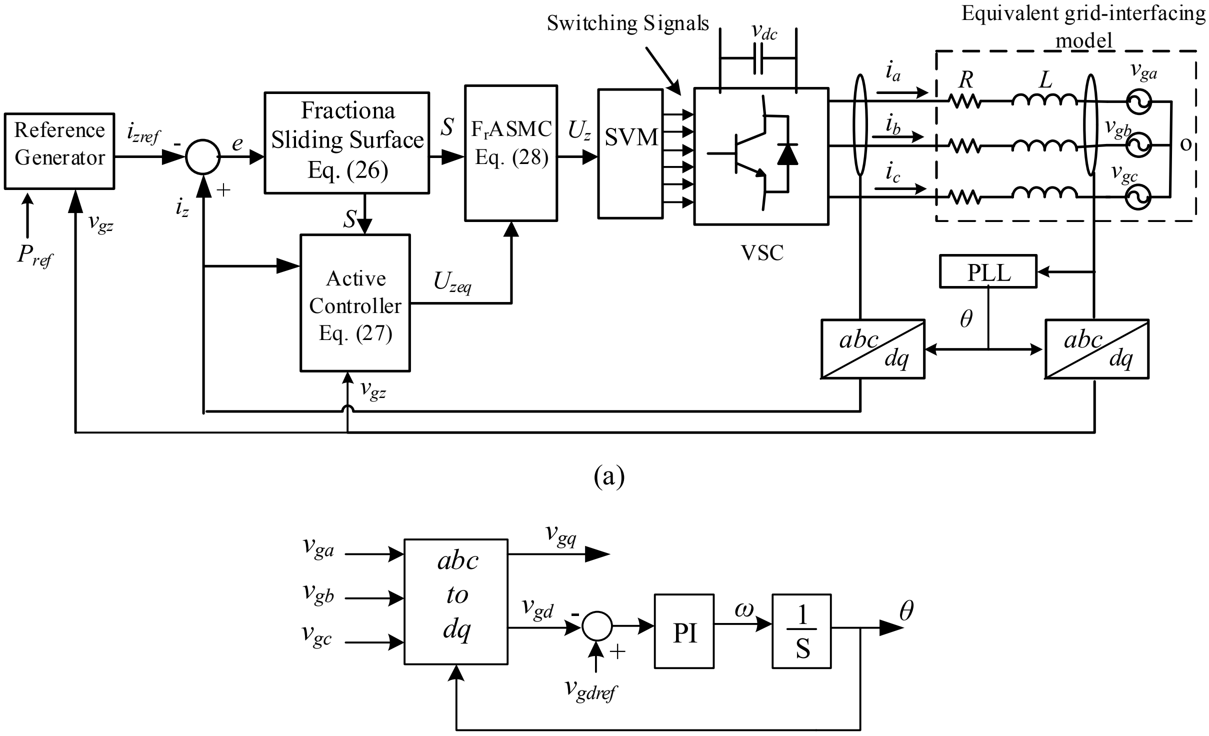

Fig. 3. (a) schematic diagram of the proposed F_rASMC for DG model, (b) Basic structure of the synchronous reference frame PLL.

As can be seen in Fig 3.a, the PLL strategy is incorporated to extract the phase angle of the grid voltage θ [31]. The PLL is implemented in *dq* synchronous reference frame, and its block diagrams are illustrated in Fig 3.b. In this structure, three-phase voltage vector is transformed from *abc* natural reference frame to *dq* rotating reference frame by using Park's transformation. A regulator, usually PI, is used to control this variable, and the output of this regulator is the grid frequency. After the integration of the grid frequency, the utility voltage angle is obtained. The angular position of the *dq* reference frame is controlled by a feedback loop which regulates the *d* component to zero [32]. In case of the grid voltage is distorted, this PLL can operate satisfactorily, nevertheless, additional improvements should be taken into consideration to overcome grid unbalances.

C. Stability analysis

By considering a Lyapunov function candidate as,

$$V = \frac{1}{2}S^2, \tag{29}$$

a sufficient condition for the states to move from the second phase to the first one in a finite time is as follows,

$$\dot{V} = S\dot{S} \le 0. \tag{30}$$

The first derivative of the fractional sliding surface can be obtained as,

$$\dot{S} = k_p D\left(x_{ref} - x\right) + k_i D D^{-\lambda}\left(x_{ref} - x\right), \tag{31}$$

which can be rewritten using the principles and properties of the fractional derivatives and integrals as follows,

$$\dot{S} = k_p\left(\dot{x}_{ref} - \dot{x}\right) + k_i D^{1-\lambda}\left(x_{ref} - x\right). \tag{32}$$

Thus, the condition (30) can be expressed as,

$$\dot{V} = S\dot{S} = S\left[k_p\left(\dot{x}_{ref} - \dot{x}\right) + k_i D^{1-\lambda}\left(x_{ref} - x\right)\right]. \tag{33}$$

Substituting (21) and (28) in (33) yields,

$$\begin{aligned} \dot{V} = S\Big[k_p\Big(\dot{x}_{ref} - A_o x - B_o\Big(-B_o^{-1}\left(A_o x + T_o v_{gx} + CS\right) + \gamma sgn(S)\Big) - T_o v_{gx} - r\Big) + \\ k_i D^{1-\lambda}\left(x_{ref} - x\right)\Big] \\ = S\left[k_p\left(\dot{x}_{ref} + CS - B_o \gamma sgn(S) - r\right) + k_i D^{1-\lambda}\left(x_{ref} - x\right)\right] \\ \le -k_p B_o \gamma |S| + \left|k_p \dot{x}_{ref} + k_p CS - k_p r + k_i D^{1-\lambda}\left(x_{ref} - x\right)\right| |S|. \end{aligned} \tag{34}$$

The term $\dot{x}_{ref}$ is equal to zero because the reference output current of the model i_{zref} ($=x_{ref}$) in *dqo*-coordinate system is a constant value. Assuming that the model operates in its normal condition, the error of the system $x_{ref} - x$ has a limited value. Thus, $k_i D^{1-\lambda}\left(x_{ref} - x\right)$ and $k_p CS$ are finite. Also according to (23), r is considered to be limited by δ. Therefore, the term $\left|k_p \dot{x}_{ref} + k_p CS - k_p r + k_i D^{1-\lambda}\left(x_{ref} - x\right)\right|$ is bounded as,

$$\left|k_p \dot{x}_{ref} + k_p CS - k_p r + k_i D^{1-\lambda}\left(x_{ref} - x\right)\right| \leq \beta, \tag{35}$$

where β is a positive constant, then the proposed model is stable when,

$$\gamma \geq \left(k_p B_o\right)^{-1} \beta. \tag{36}$$

V. Simulation results

To investigate the performance of the proposed control strategy, the simulation models have been developed under Matlab/Simulink environment. The rated rms grid phase voltage is 120 V at 60 Hz, and the nominal values of interfacing resistance and inductance are $R_o = 0.2\,\Omega$ and $L_o = 0.1\,mH$, respectively. The dc-link voltage is set to 400 V and the switching frequency of the VSC is 10 kHz. The control architecture of the overall DG interface is shown in Fig. 3.a. The reference active power is set to 3 kW.

The stability and dynamic response of the DG model will now be analyzed, and the effectiveness of the designed controller will be evaluated and compared with conventional PI synchronous-frame current controller to validate the proposed procedure.

To illustrate the effect of interfacing impedance variations on the current controller performance of a VSC-based DG system, the interfacing resistance and inductance seen by the VSC (R and L) change from [$R = 0.2\ \Omega$ and $L = 0.1\ mH$] to [$R = 0.5\ \Omega$ and $L = 0.6\ mH$] at the instant $t = 0.05$ s in simulations.

The performance of the PI current controller under above mentioned condition is depicted in Fig. 4. As can be seen, the current response cannot track the reference current properly when the interfacing impedance changes, which is consequence of the nonrobust PI current controller. Tuning the PI gains can bring the system into stability; however, it leads to degradation of disturbance rejection capability and increase in steady-state tracking error.

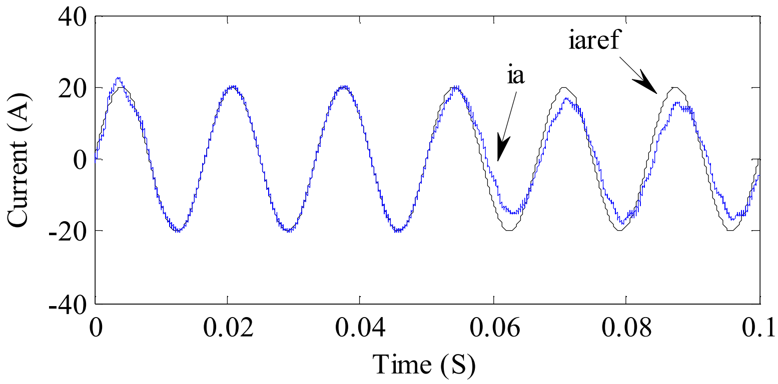

Fig. 4. Output current of VSC and its reference with conventional PI controller under interfacing impedance variation at the instant $t = 0.05$ s.

Fig. 5 shows the output current of the VSC and utility grid voltage with the proposed F_rASMC. It can be observed that the current controller remains stable and injects high quality currents in phase with the utility grid voltage when the interfacing impedance changes. From Fig. 5 the grid-connected power factor is 1.

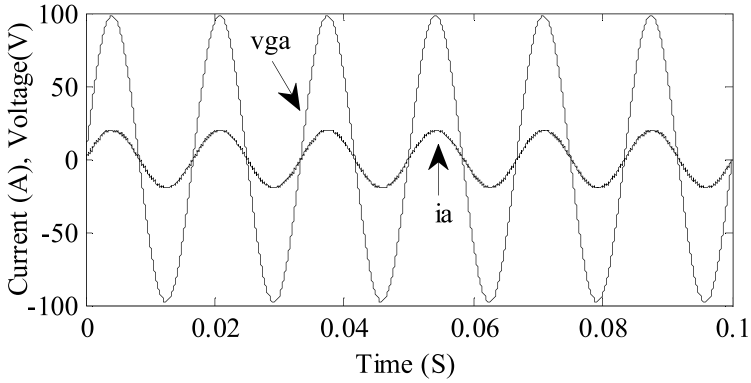

Fig. 5. Output phase a current and grid voltage of the grid-connected DG unit with the proposed F_rASMC under interfacing impedance variation at the instant $t = 0.05$ s.

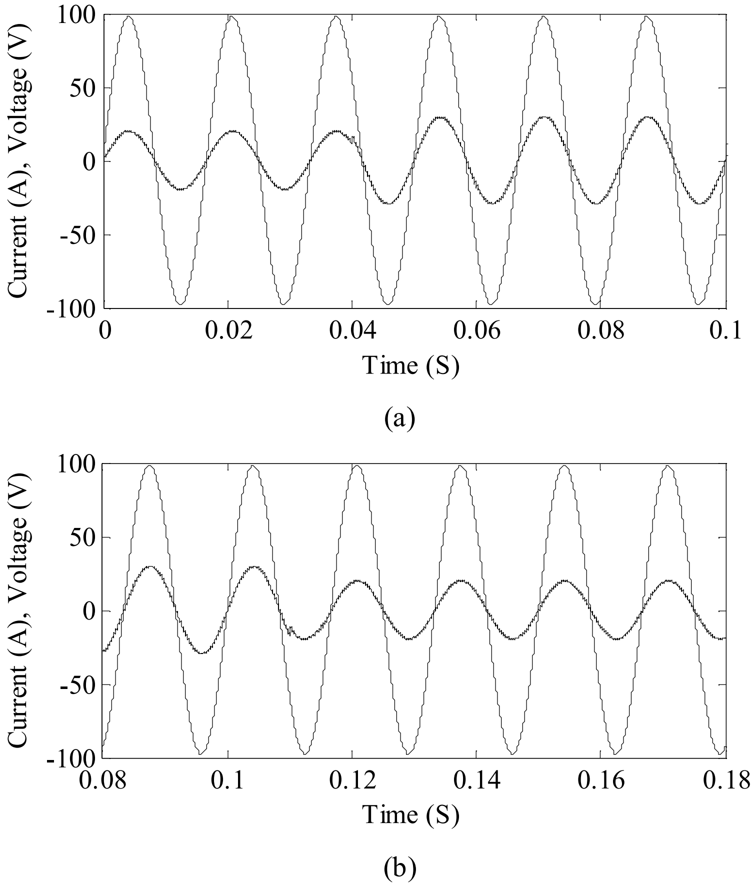

Fig. 6. Output phase a current and grid voltage of the grid-connected DG unit with the proposed F_rASMC, (a) reference active power changes from 3 to 4.5 kW, (b) reference active power changes from 4.5 to 3 kW.

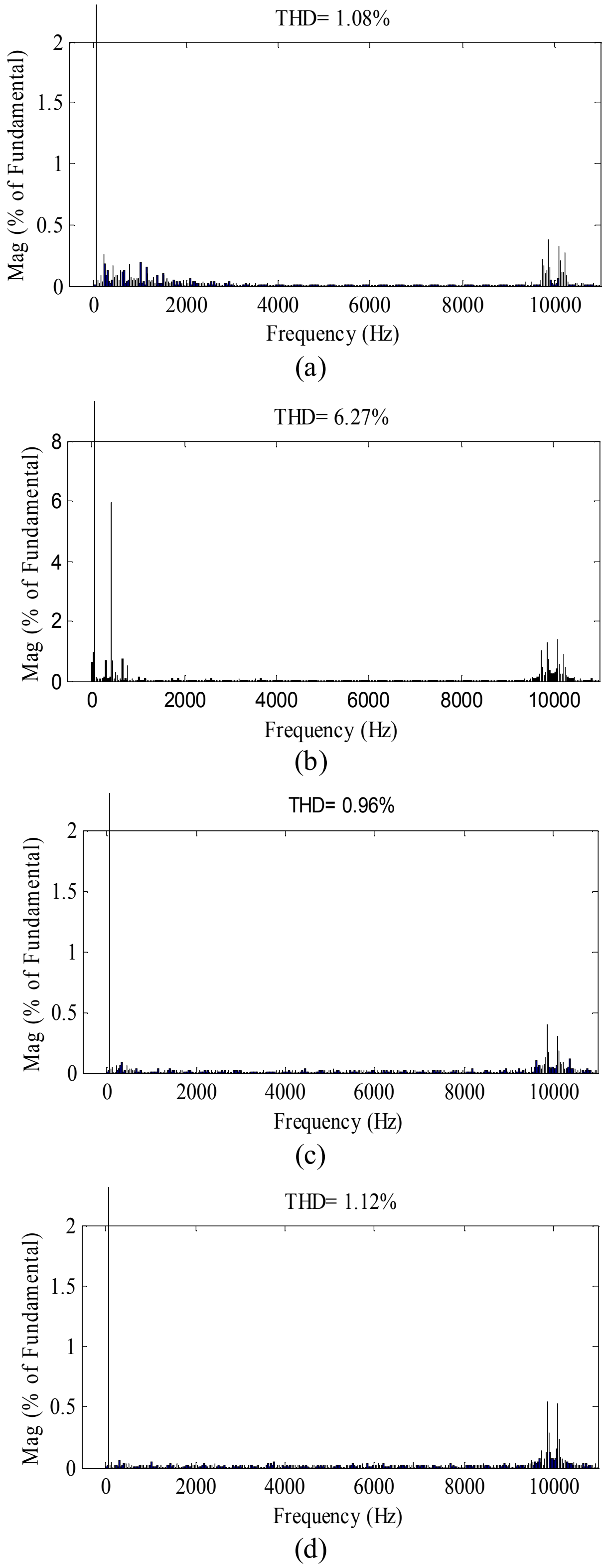

Fig. 7. Harmonic spectra of phase a VSC output current, (a) conventional PI before impedance change, (b) conventional PI after impedance change, (c) proposed F_rASMC before impedance change, (d) proposed F_rASMC after impedance change.

Fig. 6 illustrates voltage and current response of the grid-connected VSC with the proposed F_rASMC under reference active power variations along with impedance variation at $t = 0.05$ s, where the reference active power changes from 3 to 4.5 kW in subfigure (a) at the instant $t = 0.04$ s, and from 4.5 to 3 kW in subfigure (b) at the instant $t = 0.11$ s. As can be observed from Fig. 6 using the proposed control method, the grid-connected current follows the reference variation immediately and can be controlled in the stable way to be in phase with the utility grid voltage (PF=1).

Fig. 7 shows harmonic spectra of phase a current response of conventional PI and proposed F_rASMC before and after interfacing impedance change (with $P_{ref} = 3$ kW). As can be seen from Fig. 7.a, THD of output current of the conventional PI current controller before impedance change is 1.08%. However, Fig. 7.b illustrates the THD after impedance change is 6.27% which does not meet the THD requirement of the IEEE standard 1547 (that is below 5%) [33], furthermore, significant low order harmonics can be observed in the harmonic spectra. As can be observed from Figs. 7.c and 7.d, THD of VSC output current of proposed F_rASMC before and after impedance change are 0.96% and 1.12%, respectively, which demonstrates the proposed controller successfully meets the standard requirement and has a better performance than conventional PI.

VI. Conclusion

DG units are commonly integrated to the utility grid by VSCs for better controllability, reliability, and efficiency. The VSC transfers the generated power to the utility grid using a current controller which has the mission of injecting high quality currents. However, the stability of the current controller is often destroyed by the variations on the interfacing impedance seen by the VSC, such that the system becomes oscillatory or even unstable. In this paper, a F_rASMC has been proposed for integration of DG units to the utility grid. A fractional sliding surface has been developed which represents the dynamic performance of the system, then the proposed control technique has been designed in two phases; $S = 0$, when the system states are on the surface and the active controller is designed, and $S \neq 0$, when the states are not on the surface and a switching control law is developed to force the system states to reach the surface. Furthermore, this paper has analyzed the stability issue of the controller and has determined the condition in which the controller is stable. The main aim of the proposed current controller is to deliver the desired power to the grid with low harmonic current, fast response, and high power factor while maintaining the system insensitive to the interfacing impedance variations. To validate the performance of the proposed F_rASMC, simulation verification results have been presented and compared with the conventional PI current controller. The results show that high power-quality current injection is achieved with the proposed F_rASMC for integration of VSC-based DG units to the utility grid.

VII. Acknowledgements

João Catalão and Edris Pouresmaeil thank the EU Seventh Framework Programme FP7/2007–2013 under grant agreement no. 309048, FEDER through COMPETE and FCT, under FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010), UID/CEC/50021/2013 and SFRH/BPD/102744/2014.

References

[1] Akorede M F, Hizam H, Pouresmaeil E. Distributed energy resources and benefits to the environment. Renewable Sustainable Energy Rev 2010; 14(2): 724-734.

[2] Blaabjerg F, Teodorescu R, Liserre M, Timbus V A. Overview of control and grid synchronization for distributed power generation systems. IEEE Trans Ind Electron 2006;53(5):1398–1409.
[3] Carrasco J M, Franquelo L G, Bialasiewicz J T, Galvan E, Guisado R C P, Prats Ma A M, Leon J I, Moreno-Alfonso N. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Trans Ind Electron 2006; 53(4): 1002–1016.
[4] Mehrasa M, Pouresmaeil E, Mehrjerdi H, Jrgensen B N, Catalão J P S. Control technique for enhancing the stable operation of distributed generation units within a microgrid. Energy Conversion and Management 2015; 97: 362-373.
[5] Pouresmaeil E, Miguel-Espinar C, Massot-Campos M, Montesinos-Miracle D, Gomis-Bellmunt O. A control technique for integration of DG units to the electrical networks. IEEE Trans Ind Electron 2013; 60(7): 2881-2893.
[6] Blaabjerg F, Chen Z, Kjaer S. Power electronics as efficient interface in dispersed power generation systems. IEEE Trans Power Electron 2004; 19(5): 1184–1194.
[7] Kim M, Hara R, Kita H. Design of the optimal ULTC parameters in distribution system with distributed generations. IEEE Trans Power Syst 2009; 24(1): 297–305.
[8] He J, Li Y W, Munir M S. A flexible harmonic control approach through voltage-controlled DG-grid interfacing converters. IEEE Trans Ind Electron 2012; 59(1): 444–455.
[9] Mehrasa M, Pouresmaeil E, Catalão J P S. Direct Lyapunov Control Technique for the Stable Operation of Multilevel Converter Based Distributed Generation in Power Grid. IEEE Journal of Emerging and Selected Topics in Power Electronics 2014; 2(4): 931-941.
[10] Pouresmaeil E, Mehrasa M, Catalão J P S. A Multifunction Control Strategy for the Stable Operation of DG Units in Smart Grids. IEEE Trans Smart Grid 2015; 6 (2): 598-607.
[11] Liserre M, Theodorescu R, Blaabjerg F. Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values. IEEE Trans Power Electron 2006; 21(1): 263–272.
[12] Mohamed Y A I, El-Saadany E F, Salama M M A. Adaptive grid-voltage sensorless control scheme for inverter-based distribution generation. IEEE Trans Energy Convers 2009; 24(3): 683-694.
[13] Mao X, Ayyanar R. An adaptive controller for inverter-interfaced DGs connected to grids with a wide range of unknown impedances. 2010 Energy Conversion Congress and Exposition (ECCE). p. 2871 – 2877.
[14] Sun J. Impedance-based stability criterion for grid-connected inverters. IEEE Trans Power Electron 2011; 20(11): 3075–3078.
[15] Yang S, Lei Q, Peng F Z, Qian Z. A robust control scheme for grid-connected voltage-source inverters. IEEE Trans Ind Electron 2011; 58(1): 202–212.
[16] Podlubny I. Fractional-order systems and $PI^{\lambda}D^{\mu}$ controllers. IEEE Trans Autom Control 1999; 41(1): 208–213.
[17] Valerio D. Fractional robust system control. Technical University of Lisbon, Ph.D. thesis 2005.
[18] Agrawal O P. A general formulation and solution scheme for fractional optimal control problems. Nonlinear Dynamics 2006; 38(1-4): 323–337.
[19] Jelicic Z D, Petrovacki N. Optimality conditions and a solution scheme for fractional optimal control problems. Struct Multidiscip Opti 2009; 38(6): 571–581.
[20] Bartolini G, Fridman L, Pisano A, Usai E, (Eds.). Modern sliding mode control theory: new perspectives and applications. Springer Berlin 2008.
[21] Edwards C, Fossas Colet E, Fridman L, (Eds.). Advances in variable structure and sliding mode control. Springer Berlin 2006.
[22] Hosseinnia S H, Tejado I, Vinagre B M, Sierociuk D. Boolean-based fractional order SMC for switching systems: application to a DC-DC buck converter. Signal Image and Video Processing 2012; 6(3): 445-451.
[23] Hosseinnia S H, Ghaderi R, Ranjbar A, Mahmoudian M, Momani S. Sliding mode synchronization of an uncertain fractional order chaotic system. Computers and Mathematics with Applications 2010; 59(5): 1637-1643.
[24] Pisano A, Rapaic M R, Jelicic Z D, Usai E. Sliding mode control approaches to the robust regulation of linear multivariable fractional-order systems. Int J Robust Nonlinear Control 2010;20(18):2045–2056.
[25] Calderón A J, Vinagre B M, Feliu V. Fractional order control strategies for power electronic buck converters. Signal Process 2006; 86(10): 2803–2819.
[26] Efe M O. Fractional order sliding mode control with reaching law approach. Turk J Electr Eng Comput Sci 2010; 18(5): 731–747.

[27] Young K D, Utkin V I, Ozguner U. A control engineer's guide to sliding mode control. IEEE Transactions on Control Systems Technology 1999; 7(3), 328 – 342.
[28] Wang J, Li S, Yang J, Wu B, Li. Extended state observer-based sliding mode control for PWM-based DC–DC buck power converter systems with mismatched disturbances. IET Control Theory and Applications 2015; 9(4): 579 –586.
[29] Khandekara A A, Patreb B M. Discrete sliding mode control for robust tracking of time-delay systems. Systems Science & Control Engineering 2014; 2(1): 457-464.
[30] Podlubnny I. Fractional differential equations. Academic Press New York 1999.
[31] Karimi-Ghartemani M. A Novel Three-Phase Magnitude-Phase-Locked Loop System. IEEE Trans Circuits And Systems 2006; 53(8): 1792-1802.
[32] Rodríguez P, Pou J, Bergas J, Candela J I, Burgos R P, Boroyevich D. Decoupled Double Synchronous Reference Frame PLL for Power Converters Control. IEEE Trans Power Electronics 2007; 22(2): 584-592.
[33] IEEE standard for interconnecting distributed resources with electric power systems, IEEE standard 1547-2003, Jul. 2003.