Optimal Model Predictive based on Super-Twisting Fractional Order Sliding Mode Control to Regulate DC-link Voltage of DC Microgrid

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Abstract:

This paper aims to essentially regulate the DC-link voltage of DC microgrid during the disturbance conditions in power system. Hence, a novel Optimal Model Predictive Super-Twisting Fractional Order Sliding Mode Control (OMP-STFOSMC) is proposed for three-phase AC-DC converter which can effectively enhance the stability and dynamic performance of microgrid. The conventional model-predictive controllers have severely imposed the dynamic stability which leads to high overshoot, undershoot and settling-time. The sliding mode controller can be replaced instead of these conventional controllers to appropriately triumph over this problem. A main drawback of conventional sliding mode controller is related to its high frequency chattering in the control signal which can affect the system and doesn't make it satisfactory and feasible for real applications. The proposed OMP-STFOSMC can effectively enhance the control tracking performance and reduce the high frequency chattering problem. The Stochastic Fractal Search (SFS) algorithm due to its high exploration and good evasion of local optima is used to optimally tune the controller parameters. Different operation conditions are considered to evaluate the dynamic and chattering-free performance of proposed controller. As to the simulation results with comparative analysis, it is observed that the proposed OMP-STFOSMC offers better dynamic stability characteristics.

Keywords: DC Microgrid, Tracking Performance, Chattering Problem, OMP-STFOSMC, SFS Algorithm

1. Introduction

Since the critical issues associated with energy, environment, sustainable development and suchlike are intrinsic and substantial components in the human welfare, so their exploitation and utilization must be optimally performed [1]. Indeed, the issue of energy provision for humans in all different life prospects is fundamental and unavoidable [2], which is at the forefront of industrial and academic concerns in developed countries [3]. Different types of energy such as heat, electricity, kinetic and chemical, etc. are directly or indirectly seen in all household, agricultural and industrial applications [4]. Energy shortage as a major challenge as well as greenhouse gas rise and environmental prolusion have led to more utilization of renewable energy sources [5].

Power electronic converters are widely used to control the generated power by the renewable energy sources, and accordingly convert it into the required electrical energy [6]. The AC-DC converters are such these devices which are known as rectifiers. These devices are extensively used in the electrical circuit of Renewable Energy Sources (RES), whereas DC microgrid is one of these applications [7, 8]. Apart from them, AC-DC converters have successfully found their roles in many industrial applications such as Power-Electronic Drives (PEDs), Power Quality Compensators (PQCs), Active Power Filters (APFs) and so forth [9-11]. AC-DC converters can be generally categorized into controllable and uncontrollable types. These devices are mainly classified according to their AC-side input, i.e. being single-phase or three-phase. In uncontrolled type, diodes are used as semiconductor switches for triggering purposes without power flow control e.g. DC speed drives. However, the controlled type aims to control the power flow via switchable semiconductors e.g. thyristor and IGBT [12, 13].

Microgrid is currently one of the most important concepts related to smart grids. A DC microgrid, either connected to the grid or islanded, can incorporate this concept directly into a DC or AC power system using inverters and relevant control strategies [14]. In other words, it is possible to create a DC link using power electronic circuits to supply the energy required for DC loads. In DC-based renewable sources such as Photovoltaic (PV), Fuel Cell (FC), Battery Energy Storage (BES) and DC terminals of electronic power circuits, DC-DC converters are just used to control the DC-link voltage [15]. But, AC-based renewable sources such as wind turbines use AC-DC converters to provide DC voltage [16]. DC microgrid systems due to high reliability, uninterruptible power supply, lack of reactive power and frequency, low power losses, high efficiency, easy connection to DC bus, no need for synchronization and increasing DC loads have received more and more attention worldwide [17]. There are many different control schemes for three-phase AC-DC converters to enhance the power quality and dynamic response under disturbance conditions [18-20]. Ref [21] proposes a new voltage tracking controller which has adopted nonlinear observers for the microgrid converters to consider the uncertainties and disturbances due to parameters variations. Also, Ref [22] proposes two new methods to share the microgrid’s current. The first method has updated the droop resistance for each converter to track the current sharing reference, and the second method has optimized the droop resistances to remove current sharing loops and relevant communications.

Among the available control schemes, Model Predictive Control (MPC) can promptly control the demand-side power with low ripples. The MPC controller for the two-level converters has been optimally designed to provide the best switching mode out of eight feasible modes to attain the desired voltage vector. In this regard, deviations between references and predicted values of control variables are considered as objective functions to be minimized [23-25]. The conventional controllers such as PID are mainly used in the MPC strategy to provide active power reference as a main term of objective function. The controller parameters must be appropriately adjusted to meet the system performance requirements and unexpected perturbations. Nevertheless, the controller parameters haven’t been adjusted during the different operating conditions.

To overcome the mentioned deficiencies, sliding mode controller has been taken into account to augment the system dynamic performance [26]. SMC is an eminent robust control strategy due to its exceptional dynamic response and inherent robustness against the parameter variations, external perturbations and unknown uncertainties [27, 28]. As for its high performance and applicability, many different industries and technologies have extensively employed SMC to assist and improve the desired system control performances. According to this control strategy, the control signal converges the state trajectory toward the sliding surface to eliminate the steady-state tracking error. All the state trajectories have been pinched around the sliding surface for defined time, afterward approaching the system equilibrium point [29]. Hence, this paper essentially aims to present SMC-based MPC to overcome the deficiencies of the conventional MPC strategy. The active power reference can be better tracked to enhance the system robustness and dynamic response. Although the SMC presents a good performance, accuracy and robustness against the parametric variations, unknown uncertainties and unmodelled dynamics, it has undergone the chattering phenomenon due sign function.

In recent years, various optimal and robust control strategies have been proposed for DC microgrid to improve the trajectory tracking and stabilization of its converter part [30-32]. A number of nonlinear control strategies have been reported to manage and control the energy systems which are based on integer order [33-35]. Fractional order controller can provide high-degree of freedom model for systems with more flexibility than integer order controller. Another effective control strategy is super-twisting controller which can be used to attain fast convergence and high robustness without loss of accuracy. The salient advantage of this strategy is to independent design of the procedure without previous constraint knowledge about uncertainties and perturbations [36, 37]. This strategy can be effectively used to decrease the chattering phenomenon due sign function.

To overcome SMC drawback, super-twisting control law and fractional order calculus have been merged with SMC scheme to enhance its system robustness and trajectory tracking accuracy. The so-called STFOSMC has augmented the MPC controllability of three-phase AC-DC converter to enhance the stability and dynamic performance of microgrid. Using this control scheme, not only the main drawback of the conventional model-predictive controllers i.e., unsuitable dynamic stability response with high overshoot, undershoot and settling-time can be solved, but also the chattering phenomena will be significantly reduced.

Although the system freedom degree is increased by super-twisting and fractional order schemes which leads to high system controllability level, but adjusting its parameters is really crucial and complex step. In recent years, many different optimization algorithms have undertaken the optimal controller design. The most well-known optimization algorithms are: Genetic Algorithm (GA) [38], Particle Swarm Optimization (PSO) [39], Local Unimodal Sampling (LUS) [40], Ant Colony Optimization (ACO) [41], Bat Algorithm Search (BAT) [42], Artificial Bee Colony (ABC) [43], Gravitational Search Algorithm (GSA) [44], Differential Evolution (DE) [45] and Teaching Learning Based Optimization (TLBO) [46] which have been widely reported in literature. Stochastic Fractal Search (SFS) is a meta-heuristic technique inspired by the process of stochastic expansion based on the fractal mathematical concept [47]. SFS utilizes the diffusion characteristics which are revealed in random fractals to figure out the search space [48]. Due its salient features, it is used to optimally tune the parameters of proposed controller. To evaluate the dynamic and chattering-free performance of proposed controller, different operation conditions are considered. As to the simulation results with comparative analysis, it is observed that the proposed OMP-STFOSMC offers better dynamic stability characteristics. The most important contributions of this paper can be presented as follows:

1- Regulating the DC-link voltage of DC microgrid during the disturbance conditions in power system

2-Suggesting a novel optimal model predictive super-twisting fractional order sliding mode control for three-phase AC-DC converter

3- Increasing the system freedom degree by super-twisting and fractional order schemes to enhance the stability and dynamic performance of microgrid

4- Applying stochastic fractal search algorithm to optimally tune the proposed controller parameters

5- Considering different operation conditions to evaluate the dynamic and chattering-free performance of proposed controller

2. Electric Microgrid Concept and Functionality

2.1. Short review

Microgrids have been structured using small-scale renewable energy sources, battery energy storages, combined heat and power plants and loads with cooperation between them to enhance the reliability, efficiency and power flow of the distribution grids. Likewise, many different studies related to microgrid control schemes such as: hierarchical droop controller [49], frequency-voltage droop controller [50], optimization technique [51] and suchlike have been reported in literature. Although microgrids are commonly designed for small-scale distributed energy systems, their complex analyses based on modeling and simulation have been highly compared with the conventional energy systems. Hence, their dynamic models have been provided and analyzed to ensure stability operation of whole microgrid systems.

2.2. AC/DC microgrid structure

According to the Fig. 1, the microgrids have functionally operated alongside of the main network, i.e.: in isolated/interconnected state without/with power exchange. As for the Fig. 1, AC/DC microgrids have been commonly executed in series, parallel, switched and complex types [52]. Fig. 1a presents the microgrid series type, where all RESs and loads are connected to the DC bus via their relevant converters. Fig. 1b presents the microgrid parallel type, where the AC bus is provided to direct connection of RESs and loads, and also DC-RESs can be connected to the AC bus via their own inverters. Fig. 1c presents the microgrid switched type, where the loads can be fed via both the DC-RESs and AC-RESs [53]. Although the microgrids are commonly used in AC, the DC microgrids have attained much reputation due to the offered advantages such as: high reliability, uninterruptible power supply, lack of reactive power and frequency, low power losses, high efficiency, easy connection to DC bus, no need for synchronization.

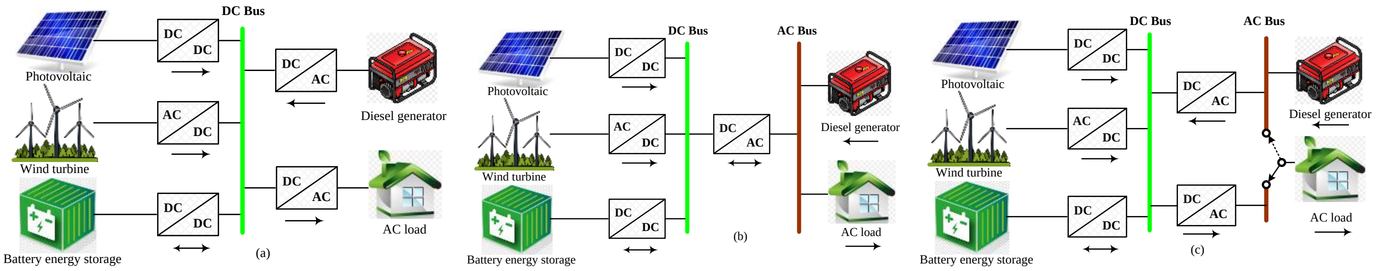

Fig. 1. AC/DC microgrid types: a) series type, b) parallel type, c) switched type

3. Model Predictive Control Design of AC-DC Converter

3.1. Model predictive control concept

This strategy has made possible limitation control and future prediction of states and control inputs. With evolution and increasing progress of the industrial automations need for industrial controllers is increased to be accurately coped with the uncertainty resulting from the model mismatches and perturbations. In other words, the conventional optimal controllers cannot be completely trusted to be applied for such these control systems. Hence, MPC scheme is presented to get ride of the need for high accuracy model, high controllable system and low computational burden.

3.2. AC-DC converter model

The electrical circuit of three-phase AC-DC converter connected to the AC system is presented in Fig. 2. The switchable semiconductors of AC-DC converter with relevant triggering strategy convert the AC voltage to the DC voltage. The series inductive filter is connected to AC side and shunt capacitive filter is connected to the DC side. The pure DC voltage can be accordingly attained. The AC-DC converter can be mathematically modeled in abc frame as follows:

$$\begin{bmatrix} L\dot{i}_a \\ L\dot{i}_b \\ L\dot{i}_c \\ C\dot{V}_{dc} \end{bmatrix} = \begin{bmatrix} -R & 0 & 0 & 0 \\ 0 & -R & 0 & 0 \\ 0 & 0 & -R & 0 \\ S_a & S_b & S_c & -1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_L \end{bmatrix} + \begin{bmatrix} V_{ga} - V_{ca} \\ V_{gb} - V_{cb} \\ V_{gc} - V_{cc} \\ 0 \end{bmatrix} \quad (1)$$

Where, R, L and C are respectively resistance, inductance and capacitance of filter. V_{ga}, V_{gb} and V_{gc} are the three-phase voltage of AC side; i_a, i_b and i_c are its relevant input currents; V_{ca}, V_{cb} and V_{cc} are the three-phase voltage of converter side; V_{dc} represents the dc output voltage; i_L represents the load current; S_a, S_b and S_c are the triggering state of the switches, while:

$$S_k = \begin{cases} 1, & upper\ \ switch\ \ on\ \ phase\ \ k\ \ is\ \ ON \\ 0, & upper\ \ switch\ \ on\ \ phase\ \ k\ \ is\ \ OFF \end{cases} \quad (2)$$

The triggering modes of AC-DC converter are essentially transferred into the $\alpha\beta$ stationary frame as follows:

$$S_{\alpha\beta} = \begin{bmatrix} S_\alpha \\ S_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{3}$$

As to the switching matrix, its relevant input voltage in $\alpha\beta$ stationary frame with respect to the dc-link can be presented as follows:

$$V_{\alpha\beta} = \begin{bmatrix} S_\alpha \\ S_\beta \end{bmatrix} = SV_{dc} = \begin{bmatrix} S_\alpha \\ S_\beta \end{bmatrix} V_{dc} \tag{4}$$

Accordingly, the dynamic model can be mathematically presented in $\alpha\beta$ stationary frame as follows:

$$V_{g,\alpha\beta} = L\dot{i}_{\alpha\beta} + Ri_{\alpha\beta} + V_{\alpha\beta} \tag{5}$$

$$C\dot{V}_{dc} = \frac{3}{2}\left(i_{g,\alpha}S_\alpha + i_{g,\beta}S_\beta\right) - I_L \tag{6}$$

Where, $V_{g,\alpha\beta}$ and $i_{g,\alpha\beta}$ respectively represent the voltage and current of the AC-side

Accordingly, the $V_{g,\alpha\beta}$ can be presented as follows:

$$\begin{bmatrix} V_{g,\alpha} \\ V_{g,\beta} \end{bmatrix} = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}\begin{bmatrix} \dot{i}_{g,\alpha} \\ \dot{i}_{g,\beta} \end{bmatrix} + \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}\begin{bmatrix} i_{g,\alpha} \\ i_{g,\beta} \end{bmatrix} + \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{7}$$

This MPC scheme aims to properly control the active and reactive power flow which can be satisfied by accurate tracking of dc-link voltage to produce the correct active power reference.

As to the space vector equation, following equation is represented:

$$\dot{x} = Ax + BV_{g,\alpha\beta} + DV_{\alpha\beta} \tag{8}$$

The AC-side current in discrete-time domain for (k+1)th instant with T_s sample time is presented as follows:

$$i_{g,\alpha\beta}(k+1) = T_s L^{-1}\left(V_{g,\alpha\beta}(k) - Ri_{g,\alpha\beta}(k) - V_{\alpha\beta}(k) + i_{g,\alpha\beta}(k)\right) \tag{9}$$

The active and reactive power is presented as follows:

$$\begin{aligned} P &= \frac{3}{2}\left(V_{g,\alpha}i_{g,\alpha} + V_{g,\beta}i_{g,\beta}\right) \\ Q &= \frac{3}{2}\left(V_{g,\beta}i_{g,\alpha}V_{g,\alpha}i_{g,\beta}\right) \end{aligned} \tag{10}$$

Also, the objective function is considered by:

$$OF = \int_0^\infty \left(\left|P - P_{ref}\right| + \left|Q - Q_{ref}\right|\right)t.dt \tag{11}$$

Where, P_{ref} and Q_{ref} respectively represent references of the active and reactive power.

The objective function is assigned to optimally extract the voltage space vector.

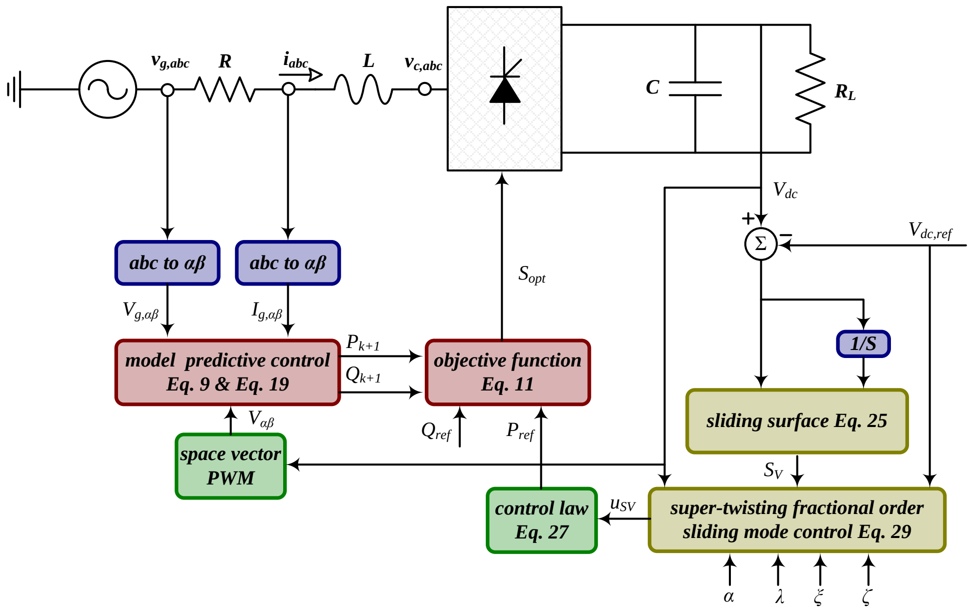

Fig. 2. General control scheme of OMP-STFOSMC.

4. Optimal Super-Twisting Fractional Order Sliding Mode Control Design for Model Predictive Scheme

Conventional controllers like PID offer weak dynamic performance with only few immutable control parameters during system operation as well as load demand and controller parameter variations. However, SMC due to its system-based design offers good dynamic performance. Despite that, it has undergone the chattering phenomenon due sign function. In this regard, super-twisting control law and fractional order calculus have been merged with SMC scheme to enhance its system robustness and trajectory tracking accuracy.

4.1. Fractional calculus principle

Fractional calculus is known as an arithmetical study with extended integral and differential to more realize the accurate system response. The general fractional order operator is given as follows [54]:

$$ {}_aD_t^{\alpha} = \begin{cases} d^{\alpha}/dt^{\alpha} & \Re(\alpha) > 0 \\ 1 & \Re(\alpha) > 0 \\ \int_a^t (d\tau)^{\alpha} & \Re(\alpha) > 0 \end{cases} \tag{12} $$

Based on the Riemann–Liouville law, the fractional integral and derivative can be presented by [54]:

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} d^{n}/dt^{n} \int_a^t (t-\tau)^{n-\alpha-1} f(\tau)d\tau \tag{13} $$

Where, n-1>α⩾ n; n is an integer number. The fractional order integral can be presented as follows:

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau)d\tau \tag{14} $$

As to simplified computational process, the fractional calculus Laplace transformation based on R–L law can be presented as follows:

$$ L\left\{ {}_aD_t^{\alpha} f(t) \right\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^{k} \, {}_aD_t^{\alpha-k-1} f(t)|_{t=0} \tag{15} $$

For n − 1 ⩾α>n without initial conditions:

$$L\{{}_aD_t^{\pm\alpha} f(t)\} = s^{\pm\alpha} F(s) \tag{16}$$

4.2. Super-twisting principle

The super-twisting algorithm has been proposed to avoid the restriction related to the high order sliding mode constraining requirement. It has been used to increase the system freedom degree with the aim of chattering reduction [55, 56]. The main advantage of this strategy over other strategies is that it doesn't require the sliding variable time derivatives. This scheme includes two parts: The first part represents the discontinuous time derivative function (i.e. u_a), and also the second part represents the continuous sliding variable function (i.e. u_b) [46].

$$u = u_a + u_b \tag{17}$$

$$\dot{u}_a = -\zeta . sat(s) \tag{18}$$

$$u_b = -\xi |s|^{\eta} sat(s) \tag{19}$$

The super twisting strategy can converge in finite time with the relevant sufficient conditions, i.e.:

$$\zeta > \frac{\phi}{\Gamma}, \quad \xi^2 \geq \frac{4\phi}{\Gamma^2} \frac{\Gamma(\zeta + \phi)}{\Gamma(\zeta - \phi)}, 0 < \eta \leq 0.5 \tag{20}$$

Where, v, μ, s_0, Φ, Γ respectively represent the corresponding positive constants. The control law is simplified by:

$$u = -\xi |s|^{\eta} sat(s) + u_a \tag{21}$$

$$\dot{u}_a = -\zeta . sat(s) \tag{22}$$

When, η=1 the super-twisting has exponentially converged to the origin.

4.3. Super-twisting fractional order sliding mode controller

Here, the purpose is to design an accurate control system to track the active power reference and preserve the dc-link voltage. To designate the dynamic process of the dc-link voltage, the instantaneous power is defined by:

$$P_i = V_{dc} i_{dc} = V_{dc} \left(C\dot{V}_{dc} + V_{dc} R_L^{-1} \right) \tag{23}$$

As to the power equilibrium assumption and neglecting the converter power losses, both the input and output instantaneous powers of converter are equal. Both the instantaneous power and active power are equal during the steady-state condition, and are proportional to the dc-link voltage. Hence, the proposed controller can control active power via dc-link voltage regulation.

Toward this subject, the tracking error is defined by:

$$e_V = V_{dc} - V_{dc,ref} \tag{24}$$

Where, $V_{dc,ref}$ represents the desired dc-link voltage. The S is taken as sliding variable with λ>0 as an arbitrary positive constant. The sliding surface can be presented as follows:

$$S_V = \lambda e_V + \int e_V . dt = 0 \tag{25}$$

With decreasing the λ, the response speed will increase and vice versa. It can be optimally tuned to as one of variables to enhance the stability and dynamic performance of microgrid. Derivative of the sliding surface leads to:

$$\dot{S}_V = \lambda \left(\dot{V}_{dc} - \dot{V}_{dc,ref} \right) + \left(V_{dc} - V_{dc,ref} \right) \tag{26}$$

As for the active power uncertainty, the control law is defined by:

$$u=\begin{cases}P_{dc}^{+}(t), & S_V>0\\ P_{dc}^{-}(t), & S_V<0\end{cases} \tag{27}$$

Where, u indicates the control law, $P_{dc}^{+}(t)$ and $P_{dc}^{-}(t)$ are respectively the positive and negative instantaneous powers during reaching the sliding variable on both sides of the sliding surface. Considering Eq. 23 and Eq. 27, derivative of the dc-link voltage is attained as follows:

$$\dot{V}_{dc}=\frac{u}{CV_{dc}}-\frac{1}{R_L C}V_{dc} \tag{28}$$

Finally, the proposed controller can be designed as follows:

$$u_{S_V}=CV_{dc}\left[\left(\frac{1}{R_L C}-\frac{1}{\lambda}\right)V_{dc}+\frac{1}{\lambda}V_{dc,ref}-\xi|S_V|^{0.5}sat(S_V)-\zeta D^{-\alpha}sat(S_V)\right] \tag{29}$$

Where, the λ, ξ, ζ and α must be optimally tuned to enhance the stability and dynamic performance of microgrid.

Despite many benefits for super-twisting and fractional order controllers, there are some limitations for them which are mentioned as follows:

Although, the super-twisting controller allows the sliding surface along with its derivative to promptly converge to zero, the uncertainties and external perturbations must be accurately estimated which is not easy. In high-order systems, high-order super-twisting version must be applied which is not easy to tune their numerous parameters. Hence, its robustness and finite-time convergence must be accurately designed and guaranteed against the uncertainties and external perturbations so that the chattering phenomenon can be effectively suppressed. Although, the fractional order controller has been characterized with a high-degree of freedom to enhance the system control performance, adjusting its parameters is more complicated than integer order ones. Of course, this problem can be solved by some tuning methods or optimization algorithms. The realization of fractional order controller needs advanced systems with high memory capacity since it has been approximated with high-order transfer function. Due to lack of an exact approach for realization of fractional order controller, approximation methods must be essentially implemented. Stochastic fractal search algorithm

Stochastic Fractal Search (SFS) is a meta-heuristic technique inspired by the process of stochastic expansion based on the fractal mathematical concept [47]. SFS utilizes the diffusion characteristics which are revealed in random fractals to figure out the search space [48]. Due its salient features, it is used to optimally tune the parameters of proposed controller. The SFS operation has been structured based on two computational processes i.e., diffusion and updating processes which have been described as follows:

A. Diffusion process

In this process, each particle has been scattered in vicinity of its own area in a way that increases the exploitation capability of the search space. This operation strategy has significantly increased the searching capability to attain the global minima and local minima prevention. Also, Gaussian distribution is employed to produce new particles. To produce new particles, Gaussian walk is used based on the following equations [57]:

$$\begin{cases}X_{inew,1}^{d}=Gaussian\left(\mu_{X_{best}},\sigma\right)+\left(\varepsilon.X_{best}-\varepsilon',X_i\right) & if \quad rand<W\\ X_{inew,1}^{d}=Gaussian\left(\mu_X,\sigma\right) & Oherwise\end{cases} \tag{30}$$

Where, $\mu_{X_{best}}=|X_{best}|,\mu_X=|X_i|$. The standard deviation can be defined by:

$$\sigma = \left| \frac{log(g)}{g} . (X_i - X_{best}) \right| \tag{31}$$

B. Updating process

This process includes two statistical items wherein the one impacts each individual and other impacts all particles. On the other hand, all particles have been ranked based on their fitness values and the probability of each particle X_i can be expressed as follows [57]:

$$P_{a_i} = \frac{rank(X_i)}{NP} \tag{32}$$

For each particle X_i, the j^{th} part of X_i can be calculated by [57]:

$$X_i'(j) = \begin{cases} X_r(j) - \varepsilon.(X_t(j) - X_i(j)) & if \;\; P_{a_i} \le rand[0,\, 1] \\ X_i(j) & Otherwise \end{cases} \tag{33}$$

In the same way, the all particles obtained from the previous process have been ranked and allotted the relevant probability based on Eq. (16), and accordingly the below equation has been used to update the process [57]:

$$X_i'' = \begin{cases} X_i' - \varepsilon'' \times (X_t' - X_{best}) & if \;\; P_{a_i} \le rand[0,\, 1] \;\; and \;\; \varepsilon' \le 0.5 \\ X_i' + \varepsilon'' \times (X_t' - X_r') & if \; P_{a_i} \le rand[0,\, 1] \;\; and \;\; \varepsilon' > 0.5 \\ X_i' & if \; P_{a_i} \le rand[0,\, 1] \end{cases} \tag{34}$$

If the fitness value of X_i'' becomes greater than one of X_i', X_i' must be substituted by X_i''; else is retained.

C. Chaotic map

A uniform distribution function is uses to randomize the particle generation. Even so, this function has a major drawback to unravel the complex and multi-objective optimization problems which is solved by replacing the uniform distribution ε with several chaotic maps.

The Gaussian term of the new adjusted location of particle X_i at d^{th} diffusion can be represented bas follows based on the chaotic variable *cv*:

$$X_{inew,1}^{d} = Gaussian(\mu_{X_{best}}, \sigma) + (\varepsilon.X_{best} - cv, X_i) \tag{35}$$

Also, the chaotic variable *cv* has been simultaneously replaced with ε to present the new adjusted location of i^{th} particle:

$$X_i'(j) = X_r(j) - cv.(X_t(j) - X_i(j)) \tag{36}$$

The SFS algorithm flowchart is presented in Fig. 3.

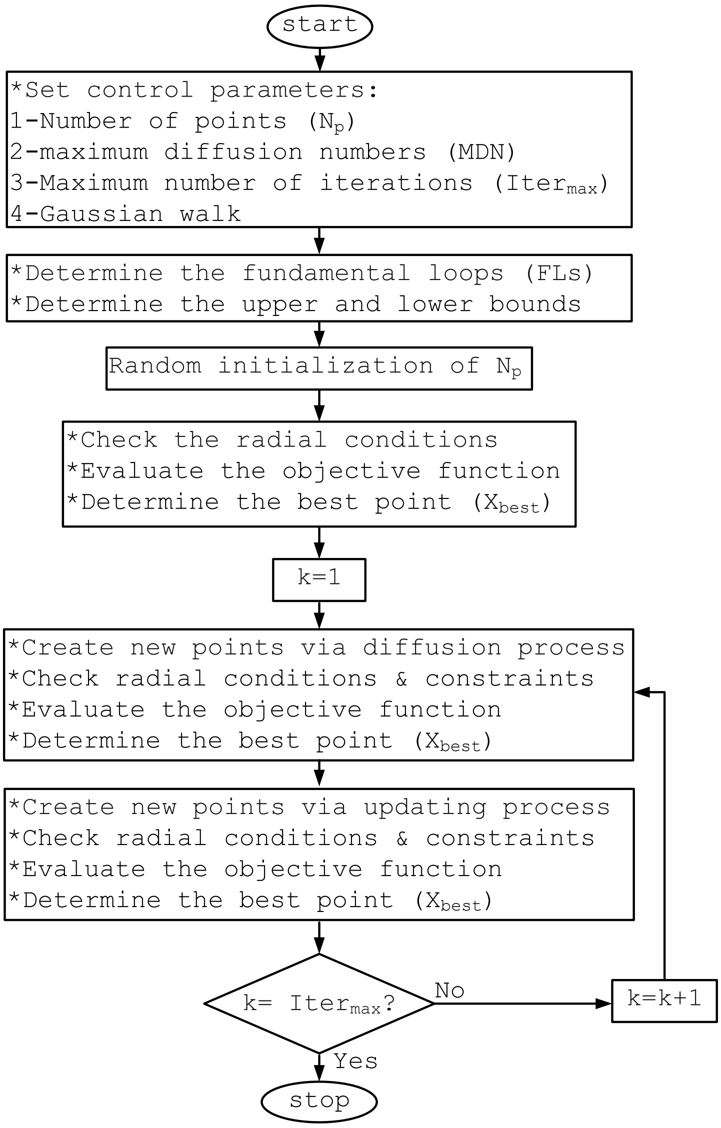

Fig. 3. SFS algorithm flowchart

5. Simulation Results and Discussion

In this part of the study, the mentioned power system along with the conventional and proposed MPC schemes has been simulated by MATLAB/Simulink software. The main system parameters are presented in Table 1. It is worth mentioning that the nominal dc-link voltage is 150 V, and also the reference reactive power is considered to be zero. To evaluate the dynamic and chattering-free performance of proposed controller, different operation conditions are here considered.

Table 1. The main system parameters

Parameter		Value
R	Filter resistance	0.35 Ω
L	Filter inductance	20 mH
C	Filter capacitor	680 µF
R_L	Load resistance	140 Ω
V_{LL}	Network voltage	380 V
f	Network frequency	50 Hz
V_{dc}	DC-link voltage	750 V
T_s	Sample time	50 µs
i_L	Nominal line current	77 A
i_C	Nominal DC-link current	73 A
f_{sw}	Switching frequency	5 kHz

N_{SW}	Number of IGBT	6
λ	STFOSMC time constant	0.045
ξ	STFOSMC super-twisting gain	0.034
ζ	STFOSMC super-twisting gain	0.012
α	STFOSMC fractional-order gain	0.83

5.1. Load voltage change

To evaluate the dynamic performance of the understudy controller, it is considered that the dc-voltage to be changed in step form. This condition occurs at t = 0.2 s with increase of 750 volts to 1000 volts, whereas it returns to its nominal value after 1.5s. The simulation results under this condition are presented in Fig. 4. It is clear that, the SMC-based MPC can better track the dc voltage reference than the PID-based MPC as well as more quickly reaching time for active power dynamic response. On the other hand, the proposed STFOSMC-based MPC can confirm its dynamic and chattering-free performance which achieved by increasing the system degree freedom and optimal tuning the controller parameters.

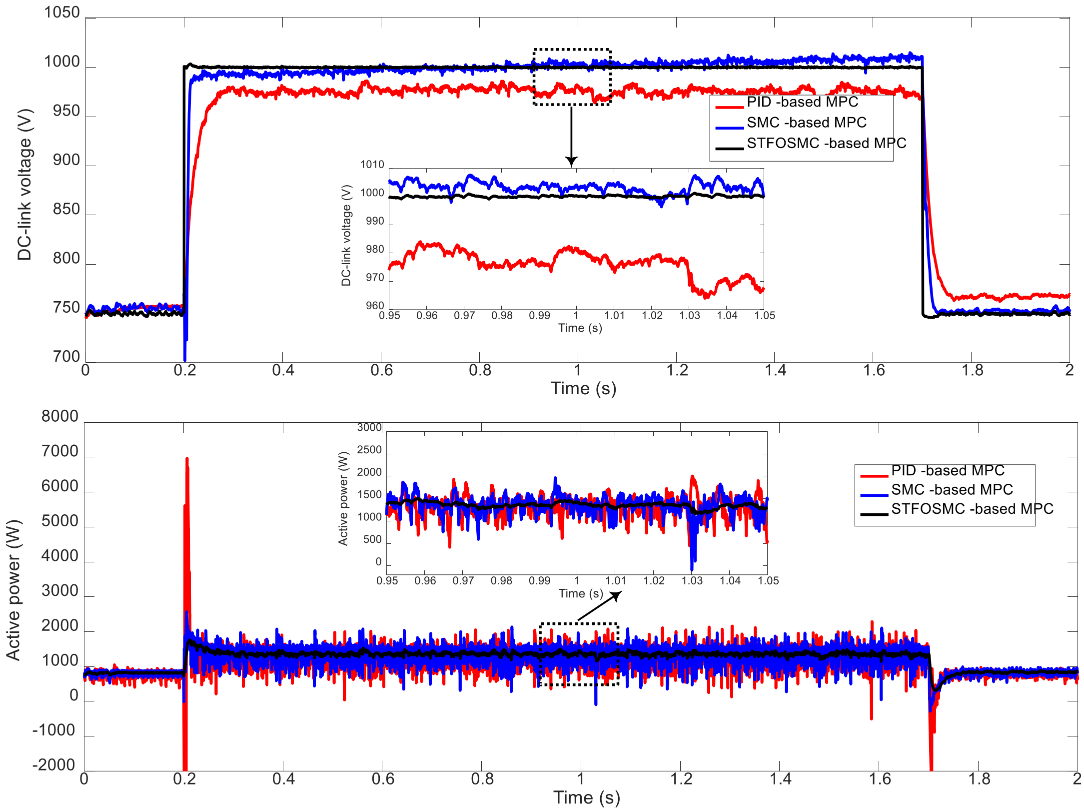

Fig. 4. Power system responses under load voltage change: a) dc-link voltage, b) active power

5.2. Load resistance change

In this section, it is considered that load resistance to be suddenly increased twice its own value at t=0.2s. The simulation results under this parameter variation are presented in Fig. 5. According to the sliding mode control design based on the system model, the dc voltage has evaded from the sudden parameter variation. Nevertheless, the PID controller cannot retrieve the nominal dc voltage in the limited time. Furthermore, the proposed STFOSMC can enhance the sliding mode control design and remove its drawbacks. As can be seen in these figures, the proposed controller can effectively and quickly track the signal references with free-chattering and robustness.

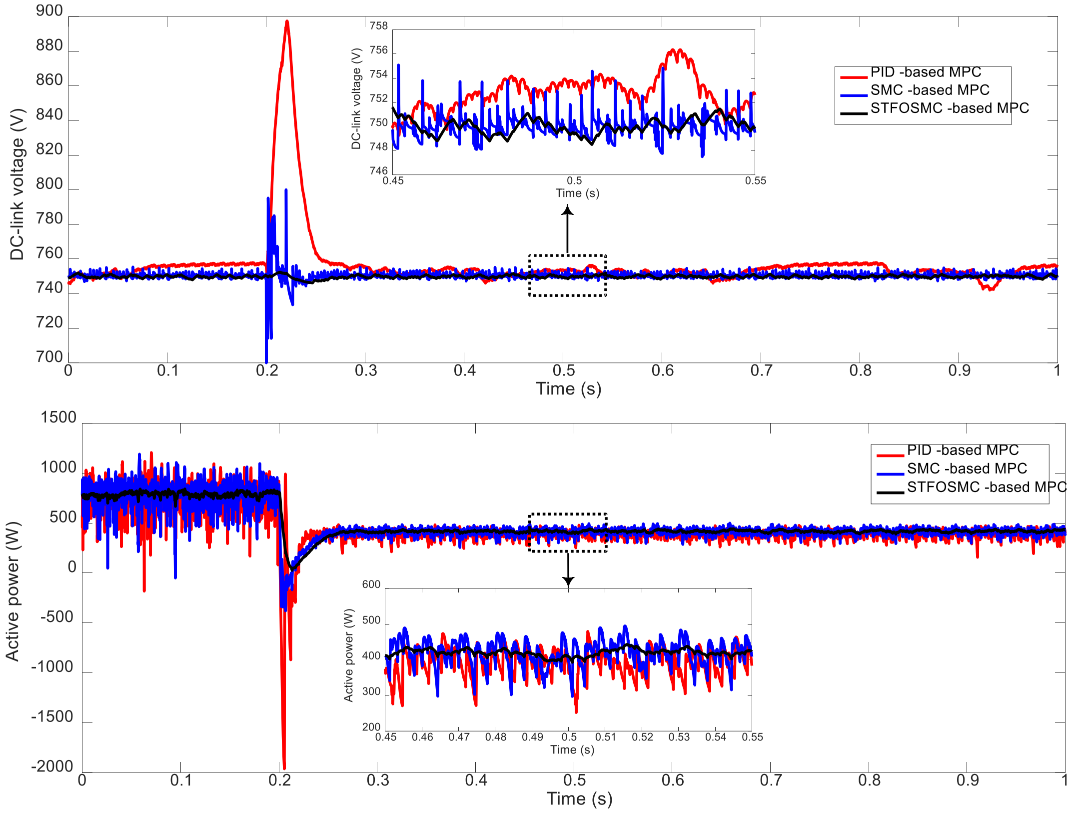

Fig. 5. Power system responses under load resistance change: a) dc-link voltage, b) active power

6. Conclusion

This paper presents a novel OMP-STFOSMC for AC-DC converter to accurately track the DC-link voltage of DC microgrid and active power dynamic reference. To overcome the chattering phenomenon of SMC, super-twisting control law and fractional order calculus have been merged with SMC scheme to enhance its system robustness and trajectory tracking accuracy. The proposed STFOSMC has augmented the MPC controllability of three-phase AC-DC converter to enhance the stability and dynamic performance of microgrid. To provide a robust controller with reliable parameters, the control problem has been designed based on an optimization problem. Due to high exploration capability and good evasion of local optima related to the SFS algorithm, it is chosen to optimally tune the controller parameters. Also, two operation conditions i.e.: load voltage change and load resistance change are considered to evaluate the dynamic and chattering-free performance of proposed controller. The simulation results under these operation conditions reveal the excellent dynamic performance for proposed STFOSMC-based MPC.

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