SECOND ORDER SLIDING MODE CONTROL FOR ISLANDED AC MICROGRIDS WITH RENEWABLE POWER RESOURCES

NAVID REZA ABJADI1, ABBAS KARGAR1

Keywords: Microgrid (MG); Master-slave strategy; Power control; Second order sliding mode control; Voltage control.

Microgrids have attracted much attention and are the future of power systems. This paper proposes a new control scheme for islanded ac microgrid (MG) using the master-slave technique. Stability and high performance are vital for islanded MG. Two second order sliding mode controls (SMCs) are designed in stationary reference frames for master and slave units to control voltage and power. Both designed controls guarantee the convergence of considered outputs to their reference values. The proposed controls are robust, simple, and chattering-free, and only require local measurements. The control method proposed in this paper can be easily extended to microgrids with any number of slave units and parallel connected inverters. The effectiveness of the proposed control scheme is verified through simulation results in MATLAB/Simulink environment and compared to feedback linearization control and a modified conventional SMC.

1. INTRODUCTION

Climate change and environmental pollution caused by fossil fuels cannot be ignored. Green energy sources can be used to overcome these problems. Distributed generation (DG) sources such as wind turbines and photovoltaic systems will play an important role in future power systems. The increasing penetration of DGs needs new approaches and solutions to improve designs and electricity utilization. Most DG sources are interfaced to the network through a voltage source inverter (VSI).

An MG is a group of connected power sources and loads [1]. MGs can provide grid demand, improve power quality, and guarantee electrical continuity to local loads in grid faults [2]. In [1], a grid-connected MG is investigated, and a control scheme is proposed under unbalanced conditions. MG can be employed by DG sources where power transmission is far away, or the MG is disconnected from the main grid because of a fault. In this case, the MG is called islanded MG [3]. In [4], a voltage and frequency control approach is proposed for DGs in islanded MG based on proportional-integral (PI) control. In [5], two additional control signals are generated to improve the stability of an MG by applying a small signal approach. Both proposed control schemes of [4,5] suffer from large overshoots and oscillations considering large disturbances.

Different strategies fall into two main categories: to control the DGs and to share the power between DGs in an isolated MG, which are communication-free and communication-based strategies [6,7]. Droop control is a communication-free strategy that only needs local information [8]; however, it doesn’t have a fast response, and it may cause some stability problems. A medium voltage MG is studied in [9,10] and employing a droop control strategy, the control and power sharing between DGs are achieved under balanced and unbalanced conditions. DC bus voltage deviation is also a main disadvantage of the conventional droop control [11]. The main communication-based strategies are centralized control, distributed control, and master-slave (MS) strategy. Centralized control needs all the information, and with a small failure, the whole system crashes. Distributed control and MS strategy need less MG information, so a low bandwidth link is necessary. MS strategy can result in very good power sharing and can be implemented easily [6,7].

In the MS strategy, the largest DG, the master unit (MU), is considered, and the other DGs are the slave units (SU). The MU controls the voltage and frequency, while each SU controls its generated active and reactive powers [6]. It can be shown that the MS strategy can be used well in parallel inverters, and it can also be used in islanded multi-bus ac MGs; however, the performance is degraded when the magnitudes of the line impedances are high since the voltages of the SUs are not controlled directly. In [2], some power-sharing issues of MS strategy are addressed, and the communication needed in MS control is discussed. In [12], a two-level control strategy for MS control MG is introduced, which does not have a good dynamic response and isn’t robust against uncertainties and disturbances.

In [6], adopting the MS strategy using PI control, the effect of communication delay in a simple MG, which included two parallel inverters, is investigated. The PI control tuning depends on the operating point of the DGs.

A communication-free master-slave MG is presented in [3]. In [13], μ-synthesis is used for MG MS control. The problem is that μ-synthesis using DK iteration is usually high order and a sophisticated design with large matrices is needed. In [14], using small signal quantities, the influence of coefficients of conventional decoupling controls with PI controllers in MS control is investigated. In [15], a cascaded PI-based voltage and current control using the MS strategy in islanded MG is investigated.

Conventional sliding mode control (SMC) is a robust nonlinear control technique commonly using a discontinuous term in control law to achieve high-performance behavior despite uncertainties. SMC can be implemented easily and can be used for trajectory tracking problems. In [16], an adaptive SMC is designed to control the voltage of the bus connected to the MU, and an adaptive feedback linearization (FBL) control is designed to control each SU’s active and reactive powers. The proposed adaptive SMC of [16] estimates the bounds of lumped uncertainties. There is no guarantee that the estimated bounds converge to their real values. Large, estimated bounds, multiplied by the sign or saturation functions, result in high control effort and much chattering. In addition, lumped uncertainties are also considered in the designed adaptive FBL control [16]. Again, large estimated lumped uncertainties cause high control effort.

High-order SMCs are robust controls that can eliminate the chattering effect [17]. In [18], implementation of two second-order SMCs for a buck converter is investigated, and it is

1 Faculty of Engineering, Shahrekord University, Shahrekord, Iran.

Emails: abjadi.navidreza@sku.ac.ir (*corresponding author), kargar@sku.ac.ir

DOI: 10.59277/RRST-EE.2023.69.1.7
shown that the chattering effect is quite reduced, and a high-performance control response is obtained. In [19], some high-order SMCs are designed for an MG adopting a centralized control scheme which is very complicated and must be redesigned if the loads or the DGs change.

Super-twisting algorithm (STA) is a continuous 2nd-order SMC without chattering phenomena which can be used to achieve a robust control [20]. STA is suitable for perturbed systems with relative degree one [21]. The algorithm with the prescribed law of variation (PLV) is another continuous 2nd-order SMC suitable for systems with relative degree two [17].

In this paper, the focus is on the control of DGs of an islanded MG using the MS strategy. Two types of 2nd-order SMCs are designed for master and slave units. To control the bus voltage connected to MU, PLV control is designed and to control the active and reactive powers delivered by SUs, STA control is used. There is a symmetry in control design since for both master and slave units 2nd-order SMCs are used. The novelty and contributions of the paper are the design of two different 2nd-order SMCs, one for MU and the other for SUs with perfect tracking, robustness, and chattering-free properties despite the simple structure of the controls. The organization of the paper is as follows: Section 2 represents the state-space model of the DGs and their appropriate controls. In section 3, simulation results are presented and discussed. Finally, section 4 states the main conclusions of the paper.

2. DGS MODELING AND CONTROL

A DG unit including VSI and LC filter is shown in Fig. 1. Applying Kirchhoff’s voltage and current laws in the stationary reference frame, one can obtain

\[
di_f/dt = a(v_f - b_i_f - v_i), \tag{1}
\]

\[
dv_f/dt = c(i_f - i_o), \tag{2}
\]

where \(i_f = [i_{fa} i_{fb}]^T\), \(v_f = [v_{fa} v_{fb}]^T\), \(v_i = [v_{fa} v_{fb}]^T\), \(a = 1/L_f\), \(b = R_f\) and \(c = 1/C_f\).

The active and reactive powers injected into the filter bus are given by [14]

\[
P = 1.5(v_{fa}i_{fa} + v_{fb}i_{fb}), \tag{3}
\]

\[
Q = 1.5(v_{fa}i_{fa} - v_{fb}i_{fb}). \tag{4}
\]

Because of the robustness, chattering-free property, and simplicity of 2nd-order SM controllers; two versions of these controllers are designed for master and slave units. Besides, feedback linearization control and a modified conventional SMC are also presented. The nth-order SM is determined by \(s = \dot{s} = \ddot{s} = s^{(n-1)}\), where \(s\) is the sliding variable [17].

![Fig. 1 – A DG unit including VSI and LC filter.](image)

Figure 2 illustrates the phase trajectories of two 2nd-order SMCs namely the super twisting algorithm and the prescribed law of variation [17]. It is seen that the trajectories achieve origin smoothly in both controls.

![Fig. 2 – Phase trajectories of two 2nd-order SMCs named (a) super twisting algorithm and (b) prescribe law of variation [17].](image)

2.1 MU 2ND-ORDER SMC DESIGN

Consider the following vector including sliding variables

\[
\dot{S} = v_f - v_i', \tag{5}
\]

where \(S = [S_a S_b]^T\) and \(v_i'\) is the voltage reference vector.

Differentiating \(S\) twice with respect to time and substituting from (1) and (2),

\[
\ddot{S} = \dot{v}_f - \dot{v}_i' = c(d_i_f/dt - di_o/dt) - v_i'' = ca(v_f - b_i_f - v_i) - cdi_f/dt - \dot{v}_i'. \tag{6}
\]

In (6), \(v_i\) is the control input and the relative degree is 2; therefore, a PLV SMC can be designed.

Considering nominal parameters and equating \(\dot{S}\) from (6) to 0, the equivalent control law is obtained as

\[
v_{ieq} = \dot{b}_i_f + v_f + (\dot{c}_d_i_f/dt + \dot{v}_i')/(\dot{c}a) \tag{7}
\]

where \(a, b\) and \(c\) are the nominal values of \(a, b\) and \(c\) respectively. The reaching control law based on the PLV method is given by [19]

\[
v_{reachable} = -V_m\text{sgn}(S + \gamma|S|^2\text{sgn}(S)), \tag{8}
\]

where \(V_m\) and \(\gamma\) are positive constants.

The control law is given by

\[
v_i = v_{ieq} + v_{ieq}. \tag{9}
\]

It is worthwhile to note that if \(v_i\) is chosen as follows, an FBL control or a modified conventional SMC is obtained

\[
v_i = v_{ieq} - K_1\dot{S} - K_2S, \tag{10}
\]

\[
v_i = v_{ieq} - K_1\text{sgn}(S) - K_2S, \tag{11}
\]

where \(K_1\) and \(K_2\) are positive constants.

2.2 SU 2ND-ORDER SMC DESIGN

Differentiating active and reactive powers from (3) and (4) concerning time and substituting from (1) and (2), one can obtain

\[
\dot{p} = f_f + u_p, \tag{12}
\]

\[
\dot{q} = f_q + u_q, \tag{13}
\]

where

\[
f_f = 1.5c[(i_{fa} - i_{oa})i_{fa} + (i_{fb} - i_{ob})i_{fb}] - 1.5a[(b_{fa} + v_{fa})v_{fa} + (b_{fb} + v_{fb})v_{fb}], \tag{14}
\]

\[
u_p = 1.5a(v_{fa}i_{oa} + v_{fa}i_{ob}), \tag{15}
\]

\[
f_q = 1.5c[(i_{fa} - i_{oa})i_{fa} + (i_{fb} - i_{ob})i_{fb}] - 1.5a[(b_{fa} + v_{fa})v_{fa} + (b_{fb} + v_{fb})v_{fb}], \tag{16}
\]

\[
u_q = 1.5a(v_{fa}i_{oa} - v_{fa}i_{ob}). \tag{17}
\]

Consider the following sliding variables

\[
\dot{p} = P - P^*, \tag{18}
\]

\[
\dot{q} = Q - Q^*. \tag{19}
\]

Differentiating (18) and (19) concerning time and substituting from (12) and (13), one can obtain

\[
\dot{S}_p = f_f + u_p, \tag{20}
\]

\[
\dot{S}_q = f_q + u_q. \tag{21}
\]
In (20) and (21), $u_p$ and $u_q$ are the control inputs and the relative degrees are 1; therefore, a STA SMC can be designed. Considering nominal parameters and equating $\dot{S}_p$ and $\dot{S}_q$ from (20) and (21) to 0 the equivalent control laws are obtained as

$$u_{peq} = -\hat{f}_p,$$  
$$u_{qeq} = -\hat{f}_q,$$

(22)
(23)

where $\hat{f}_p$ and $\hat{f}_q$ are the nominal values of $f_p$ and $f_q$ respectively.

The reaching control law based on the STA method is given by [19]

$$u_{reach} = -K_3 \int sgn(S_i) \, dt - K_4 |S| sgn(S),$$  

(24)

where $i \in \{P, Q\}; K_3$ and $K_4$ are positive constants and $0 < \delta < 1$. The control law is given by

$$u_t = u_{eq} + u_{reach},$$

(25)

It is worthwhile to note that if $u_t$ is chosen as follows, an FBL control or a modified conventional SMC is obtained

$$u_t = u_{eq} - K_4 S_t,$$

(26)

$$u_t = u_{eq} - K_3 sgn(S_t) - K_4 S_t.$$  

(27)

### 3. SIMULATION RESULTS

To investigate the validity of the designed 2nd-order SMCs for the islanded MGs, the MG of [9,10,16] is simulated in MATLAB/Simulink which is presented in Fig. 3.

This case represents the normal testing conditions for the proposed controls. Only the MU provides the powers from $t = 0$ s to $t = 0.1$ s. From $t = 0.1$s to $t = 0.15$ s the active and reactive powers of SU change from 0 to 0.2 pu and 0.1 pu linearly, respectively.

DG1 and DG2 are considered as MU and SU respectively. For simplicity such an MG is studied; nevertheless, the models and controls can be used for MGs with any number of DGs. Figure 4 shows the Simulink block diagram. The solver is the fixed-step type with a discrete sample time of 5μs. The fixed-step discrete solver with a suitable sample time results in a fast and accurate simulation. The parameters of the MG are given in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The parameters of the MG</th>
</tr>
</thead>
<tbody>
<tr>
<td>The nominal (base) power</td>
<td>3 MVA</td>
</tr>
<tr>
<td>VSIs line to line nominal voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>MG frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>VSIs filter resistance</td>
<td>0.002 Ω</td>
</tr>
<tr>
<td>VSIs filter inductance</td>
<td>500 μH</td>
</tr>
<tr>
<td>VSIs filter capacitance</td>
<td>400 μF</td>
</tr>
<tr>
<td>VSIs DC bus voltage</td>
<td>1500 V</td>
</tr>
<tr>
<td>VSIs Switching frequency</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Line1 impedance</td>
<td>0.35+j0.785 Ω</td>
</tr>
</tbody>
</table>

The master DG nominal power and the VSIs line-to-line nominal voltage are base values. The MG is tested and examined under four different cases. The parameters of the controllers are given in Table 2.

### 3.1 CASE 1

The simulation results including the voltage, active and reactive powers of three buses (PC1, PC2, and Load3) are shown in Fig. 5. It is seen that the powers track their references perfectly, and as the SU powers increase, the MU powers decrease. The voltages are sinusoidal, and the MU bus amplitude and frequency are controlled properly. At $t=0.3$s the active and reactive powers of SU change to zero and the MU provides all the demand power. No voltage deviation is observed, and the dynamic responses are acceptable without low-frequency oscillations. The voltage THDs at different buses are below the 2.5 % required by IEEE 1547 and IEC 61727 standards (50 % of the current harmonic limits) [22].

### 3.2 CASE 2

In this case, all of the testing conditions are similar to the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The parameters of the controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>The proposed control scheme</td>
<td>$V_{ac}=500$, $\mu=1e4$, $\delta=0.5$</td>
</tr>
<tr>
<td>$K_3=1e5$, $K_4=1e4$</td>
<td></td>
</tr>
<tr>
<td>FBL control</td>
<td>$K_1=50$, $K_2=500$, $K_3=1e5$</td>
</tr>
<tr>
<td>Conventional SMC</td>
<td>$K_1=20$, $K_2=300$, $K_3=15$, $K_4=1e5$</td>
</tr>
</tbody>
</table>
ones described in case 1; however, the controllers are FBL controllers. The simulation results are shown in Fig. 6. Compared to case 1, there are some oscillations on active and reactive powers of MU and Load3 which are the results of the visible increase and decrease in voltages. Using FBL control, the MU voltage tracking is not as perfect as the tracking in case 1. In addition, FBL control is not a robust control against parameter uncertainties and disturbances.

3.3 CASE 3

In this case, again, all the testing conditions are like the ones described in case 1; however, the controllers are modified conventional SM controllers. The simulation results are shown in Fig. 7. The effect of chattering is very evident. The voltages and powers are affected seriously and include high-frequency content. VSI filters cannot clear these high-frequency contents. It is worthwhile to note that chattering phenomena can also excite unmodeled modes and cause instability in the practical real system; moreover, it increases the power loss of VSI.

The performance of case 1 (proposed control scheme), case 2 (FBL control), and case 3 (conventional SMC) can be compared based on various factors and indices such as their ability to accurately track the reference. In Table 3, the integral absolute error (IAE) of $\alpha$-axis voltage and $\beta$-axis voltage for the PC1 bus and active and reactive powers for the PC2 bus are represented.

<table>
<thead>
<tr>
<th>index</th>
<th>IAE of $\alpha$-axis voltage</th>
<th>IAE of $\beta$-axis voltage</th>
<th>IAE of P</th>
<th>IAE of Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed control scheme</td>
<td>7.05</td>
<td>6.5</td>
<td>1333</td>
<td>1189</td>
</tr>
<tr>
<td>FBL control</td>
<td>25.5</td>
<td>31</td>
<td>1165</td>
<td>1065</td>
</tr>
<tr>
<td>Conventional SMC</td>
<td>37.8</td>
<td>38.6</td>
<td>49170</td>
<td>28600</td>
</tr>
</tbody>
</table>

Fig. 5 – Case 1. Proposed control scheme: voltage, active and reactive power of three buses

Fig. 6 – Case 2. FBL control: voltage, active, and reactive power of three buses
3.4 CASE 4

This case is like case 1; however, a nonlinear load (rectifier) is paralleled to Load 3 at time 0.25 s. The simulation results are shown in Fig. 8. The increasing penetration of loads with power electronics converters increases harmonic distortions in the MGs due to the inherent nonlinear nature of power electronics switches. Using the proposed controls, it is seen that despite the harmonics in Line 3 current, the voltages remain sinusoidal, and the required powers are provided by MU and SU properly. Using the proposed controls, the MG operates smoothly and is acceptable. The effect of harmonic load on voltages and powers is negligible. This case illustrates the robustness of the proposed SMCs.

![Fig. 8 – Case 4. Proposed control scheme with harmonic load (rectifier): voltage, active and reactive power of three buses](image)

3.4 DISCUSSION

Thanks to the decoupling between voltage control and active/reactive powers control in MS strategy, these variables can be controlled easily. The obtained results illustrate the superiority of steady state and dynamic performance of the proposed control scheme in all considered conditions.
regarding reference voltage tracking for MU and active or reactive powers increase or decrease for SU.

The stability and tracking performance of the voltage control and active/reactive powers control are improved significantly using the proposed control scheme. The IEA indices in Table 3 prove the improvement in the reduction of the tracking errors.

It is worth noting the parameters of the different controllers are tuned by trial and error method to obtain the best desired outcomes and when the range of these parameters are obtained the control system is not very sensitive to small changes of them. The proposed control scheme is well designed and has more parameters which results in the best performance. The conventional SMC suffers from chattering phenomena which causes instability in some circumstances.

4. CONCLUSIONS

MG is an exciting system to deliver electrical power to local loads. In this paper, two 2nd-order SMCs are designed for islanded MGs with inverter-based DGs. MS strategy is employed to control the voltage amplitude, frequency, and injected powers in MG. Without dropping generality, simulation results are presented for an MG with two DGs. Three controllers (2nd-order SM, FBL, and modified conventional SM controllers) are compared for each MU and SU. The obtained results show the superiorities of the proposed 2nd-order SMCs. The voltage of the MU bus and the injected powers of the SU are controlled perfectly. By changing the loads or the power references of the SU, the remaining load demand is met by the MU and a good load sharing between VSIs is achieved. Using the proposed control scheme, during the transients, no significant overvoltage or undervoltage is observed and a good and reliable control is obtained. In addition, the volatility inherent to the DGs is addressed properly and the DGs can inject their power when available. The main advantages of the proposed control scheme are the simple structure of controllers, perfect tracking, robustness, and chattering-free properties of controllers. The designed 2nd-order SMCs can be used to control the voltage and the powers of any VSI. It is worth mentioning here that to employ the proposed control scheme in a real MG, a secondary control is needed which provides references. Also to implement the fractional orders in control terms, special considerations are needed for accurate calculations. Finally, for future research work, renewable energy resources such as photovoltaic or wind can be considered in the MG, and the proposed control scheme is investigated with the corresponding MPPT algorithms.

ACKNOWLEDGMENT

This research is supported by the Design of Photovoltaic Systems Research Core, Shahrekord University.

Received on 19 April 2023

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