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Nonsingular Terminal Sliding Mode Control for Islanded Inverter-Based Microgrids

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Abstract— *Due to the development of renewable energy and the need for sustainable electricity, AC microgrids (MGs) have received a lot of attention and the growing need for them is becoming more and more apparent. Medium voltage MGs will be very important in providing electrical energy in the near future. This paper represents a robust and effective control method with rather simple implementation capability for islanded MGs based on master-slave (MS) technique. The designed control is a type of terminal sliding mode control, which has a high response speed and good convergence with robustness against some uncertainties. Stability and high performance are very essential for islanded MGs. The designed control meets these requirements so that the output voltage of the inverter based distributed generation (DG) sources includes a very low amount of harmonics and the generated active and reactive powers track their reference values perfectly. The effectiveness of the proposed control method is evaluated by simulation in SIMULINK/MATLAB environment. The simulation results are presented considering five cases, which include feedback linearization control (FLC) and conventional sliding mode control (CSMC) of DGs, harmonic load and high impedance transmission lines simulation results. The obtained results show the perfect tracking and robustness of the proposed control scheme considering uncertainties in parameters and it is illustrated that a high accuracy power sharing between DG sources is achieved.*

Keywords—Distributed generation, master-slave strategy, voltage and power control.

1. INTRODUCTION

The negative effects of fossil fuels on the planet and the increasing need for electricity, have led to the use of renewable energies and DG sources [1]. MGs often contain of a number of power supplies which makes them flexible. DG resources can be employed in MGs and with proper controls and strategies the peak demand can be reduced; the reliability and stability against faults and disturbances and the power quality can be improved [2]. As MGs become more common and more complex, the need for better and more efficient control methods becomes more apparent [2, 3].

When the MG is connected to the grid, the frequency and voltage of different sections usually follow the grid, but when the MG is disconnected from the grid; in addition to power balance, it also needs to control and adjust voltage and frequency [4]. Recently, medium voltage MGs attracts many attentions. In [5], an islanded medium voltage MG is introduced and investigated and a proportional resonance (PR) controller with droop control strategy is designed for MG which is not robust against changes in operating point and disturbances. The control proposed in [5], may easily become unstable in transient states. The high performance control of MGs is a difficult task due to multivariable, strong coupling, and large scale model of MGs [6, 7]. In an islanded MG, there are two categories of strategies for dividing power between DGs: communication-free strategies and communication-based strategies [8]. Droop control strategy is a communication-free strategy because it only requires local data and measurements [9]; however, this strategy does not respond quickly and may cause instability. In addition, it causes DC bus voltage deviation [10]. The main communication-based strategies are: centralized control strategy, distributed control strategy and MS strategy [11]. Centralized control has a good response, but requires all the information and measurements of the DGs that are located in different parts of the MG, and with a small defect, the whole system fails [12]. In addition, it requires a high-speed telecommunication system to provide this data and information to the controller online. Distributed control and MS strategy require less MG data, so a low bandwidth link can be used. MS strategy can lead to excellent power sharing and is easily implemented [8].

In the MS strategy, the DG with the largest power capacity is considered as the master unit (MU) and the other DGs are considered as the slave units (SU). The MU adjusts the voltage and frequency of the MG and the SUs adjust their active and reactive power output [8].

In [13], some issues of power sharing of MS strategy are addressed and the required communications in MS strategy are investigated. In [1]4, a two-level control for MS strategy is proposed which does not have a good dynamic response and does not behave well in the face of uncertainties and disturbances and may become unstable. In [8], by adopting MS strategy and proportional integral control (PI), the effect of communication delay in a simple MG consisting of two parallel inverters is investigated. The adjustment of PI controllers depends on the operating points and the method is not robust. In [15], a communication-free MS strategy is introduced for a MG in which the MU is a synchronous generator and the SUs are current source inverters.

In [16], using small signal values, the effect of coefficients of conventional decoupling PI in MS strategy is analyzed. In [17], a cascaded PI based control using MS strategy in islanded MG is investigated. In [18], μ synthesis is analyzed for MG with MS strategy and then, a variable structure control is proposed. The DGs in [18] have a three-stage solid state transformer which have

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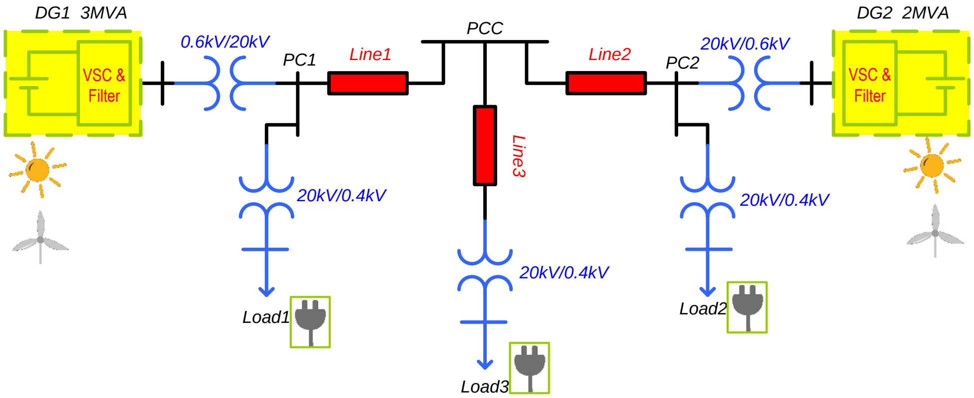


Fig. 1. A MG with inverter based DGs

a complicated structure. In [19], adopting MS strategy, an H_∞ controller is designed for the MU, but for the SUs, PI controllers are used in the dq synchronous reference frame, therefor, the overall closed-loop system will not have robust behavior, in addition to the fact that the design of the H_∞ controller is relatively complex and has several steps and matrix manipulations.

In [20], nonlinear backstepping control is used for a MG with MS strategy which needs the loads measurements. Backstepping control is a recursive method which has many steps especially when the model of DGs and their filters have models with higher orders. In addition, the proposed method in [20] is not robust.

Recently adaptive model-free controllers are introduced such as the ones use Legendre polynomials [21]. In these controllers to achieve stability and high performance, enough polynomials and coefficient should be considered and the coefficients are estimated online with adaptation laws which increase the calculations.

There are many control methods for practical problems today, among them CSMC is a method that has attracted the attention of many researchers and engineers due to its simplicity and robustness. The main problem of CSMC is the chattering phenomenon, for which various solutions have been proposed [22]. In [23] for a MG with MS strategy, adaptive SMC and adaptive feedback linearization methods have been used. Given that there is no guarantee for the convergence of estimates to real values, the amount of control effort can be high and instability may occur. In [24] using high-order SMC methods such as suboptimal second-order SMC and a third-order SMC by accepting centralized control strategy, the voltages and currents of a MG are controlled. The method of [24] is relatively complex and needs to be redesigned with the change of MG.

Other sliding mode controls (SMCs) have also been developed that have advantages over CSMCs. Terminal SMC (TSMC) is a modified SMC in which the sliding variable contains fractional order. There are two phases in SMC: the reaching phase and the sliding phase. Using TSMC both of these phases can be terminated in finite times called reaching and sliding times which can be too short by choosing design parameters [25]. In [26], a nonsingular terminal SMC (NTSMC) is introduced and is used for rigid manipulators. The NTSMC of [26] is used in [27] and [28] to control a buck converter and in [29] to control an induction motor. Two NTSMCs are designed for grid connected inverter system to control the injected current in [30] and [31].

This paper proposes robust controls for DGs of islanded MGs using MS strategy. The descriptive equations of MU and SUs are rewritten and new suitable variables are defined to conform to the NTSMC design. A NTSMC is designed for MU to control the voltage of the MU bus. Another NTSMC is designed for SUs to control the active and reactive powers delivered by SUs. There is a symmetry in control design because for both master and slave units the NTSMC are used. There are many sophisticated and optimized control methods for grid-connected inverters; the results of which are really considerable and very close to an ideal system.; however, the proposed NTSMCs for grid connected inverter with LC filter considering the resistance of filter inductor, suitable for islanded microgrid, have not been mentioned in previous research works. It is noticeable that most of the paper equations are related to obtaining the appropriate models and design of controllers, while control laws have rather simple structures and formulas, especially compared to intelligent methods or adaptive methods such as adaptive backstepping control or adaptive input-output feedback linearization, which suffer from overparametrization and complicated control and adaptation laws. The objectives of this paper are: design of two NTSMCs suitable for inverter based DGs in a microgrid with MS strategy; comparison of the proposed control scheme with FLC and CSMC; investigation the microgrid using the proposed control considering uncertainties, harmonic load and high impedance lines through computer simulations. With the proposed control, the following advantages is achieved: avoiding of sophisticated control or adaptation laws, no need of any frame transformation, perfect tracking and robustness in voltage control of master DG and power control of slave DGs.

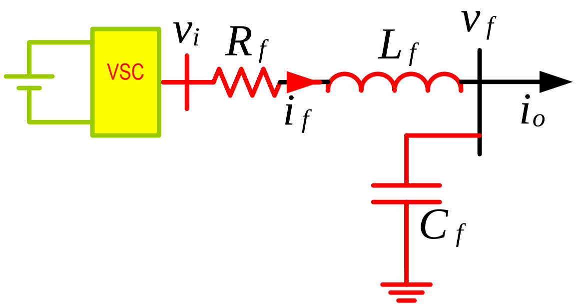


Fig. 2. An inverter-based DG unit with LC filter

2. MG CONFIGURATION AND DGS MODELING

In this section, for ease of study, an islanded MG with two inverter-based DGs are considered; nevertheless, the models, power sharing strategy and controls can be applied for MGs with any number of DGs. The MG configuration is given in Fig. 1. This configuration is used in [5], [23] and [32]. The DG with the larger capacity is selected as the MU and the other one is the SU.

An inverter-based DG unit with LC filter is shown in Fig. 2. In stationary reference frame, considering the - components of i_f and v_f as state variables, one can obtain

$$di_f/dt = a(v_i - bi_f - v_f) \tag{1}$$

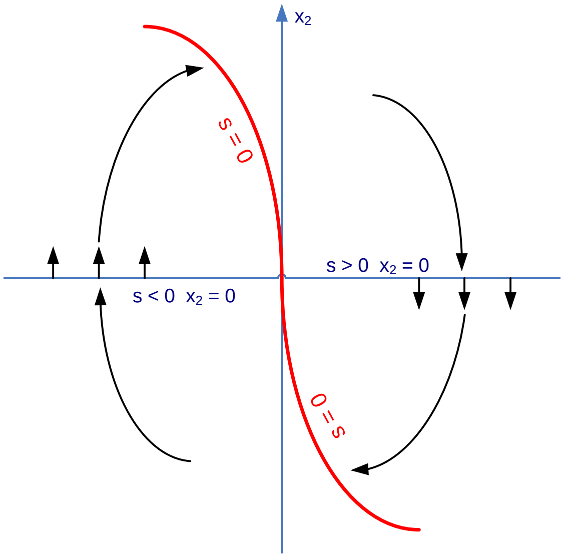


Fig. 3. Phase trajectories of NTSMC [26]

$$dv_f/dt = c(i_f - i_o) \tag{2}$$

where $i_f = [i_{f\alpha} i_{f\beta}]^T$, $i_o = [i_{o\alpha} i_{o\beta}]^T$, $v_i = [v_{i\alpha} v_{i\beta}]^T$, $v_f = [v_{f\alpha} v_{f\beta}]^T$, $a = 1/L_f$, $b = R_f$ and $c = 1/C_f$.

The powers injected into the filter bus can be calculated as [23]

$$P = 1.5(v_{f\alpha} i_{f\alpha} + v_{f\beta} i_{f\beta}) \tag{3}$$

$$Q = 1.5(v_{f\beta} i_{f\alpha} - v_{f\alpha} i_{f\beta}) \tag{4}$$

From (3) and (4), it is seen that active and reactive powers are nonlinear functions of the state variables.

3. PROPOSED CONTROLS DESIGN

3.1. NTSMC Design

A control scheme is designed for the islanded MG adopting MS strategy. The designed controls are nonsingular TSMCs which have rather simple structures but are very effective with fast response. Using TSMC, both the reaching phase and sliding phase occur in finite times. Selective control was first introduced in [26].

Consider the following second order system:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = f(x) + g(x)\,u \tag{5}$$

where $x = [x_1,\ x_2]^T$. In conventional terminal SMC, the sliding variable is defined as [26]

$$s = x_2 + \beta {x_1}^{q/p} \tag{6}$$

where β is a positive constant and p and q are positive odd numbers satisfying $p>q$.

At the end of the reaching phase, s=0 which yields

$$x_2 = -\beta {x_1}^{q/p} \tag{7}$$

substituting x_2 from (5) into (7),

$$\dot{x}_1 = -\beta {x_1}^{q/p} \tag{8}$$

Rearranging (8),

$$dt = -\frac{dx_1}{\beta {x_1}^{q/p}} \tag{9}$$

Considering $x_1(0) \neq 0$ and $x_1(t_s) = 0$, where t_s is the sliding phase time. Integrating (9) on both sides, yields

$$\int_0^{t_s} dt = -\int_{x_1(0)}^{x_1(t_s)} \frac{dx_1}{\beta {x_1}^{q/p}} \tag{10}$$

then

$$t_s = \frac{|x_1(0)|^{1-q/p}}{\beta(1-q/p)} \tag{11}$$

Eq. (11) means that the sliding phase time is finite and it can be reduced to any extent by increasing β.

The reaching condition is [22]

$$s\dot{s} < 0 \tag{12}$$

Taking time derivative of (6) and substituting it into (12), yields

$$s(\dot{x}_2 + \beta \frac{q}{p} {x_1}^{q/p-1} \dot{x}_1) < 0 \tag{13}$$

Using (5) in (13), gives

$$s(f(x) + g(x)\,u + \beta \frac{q}{p} {x_1}^{q/p-1} x_2) < 0 \tag{14}$$

The following control law with a suitable guarantees that the condition (13) is satisfied:

$$u = \overline{g}^{-1}(x)\,[-\overline{f}(x) - \beta \frac{q}{p} {x_1}^{q/p-1} x_2 - sgn(s)] \tag{15}$$

where $\overline{f}$ and $\overline{g}$ are the nominal values of f and g functions respectively.

It is seen that in the second term of (15), the power is negative and causes singularity when $x_1 = 0$ [26, 27]. To overcome this problem in [26] the following sliding variable is introduced:

$$s = x_1 + \beta^{-1} {x_2}^{p/q} \tag{16}$$

Using the sliding variable of (16), the sliding phase time becomes finite and considering the following control law, the reaching phase time is also finite [26]:

$$u = \overline{g}^{-1}(x)\,[-\overline{f}(x) - \beta \frac{q}{p} {x_2}^{2-p/q} - sgn(s)] \tag{17}$$

It is worthwhile to note that the power $2 - p/q$ in (17) is positive and there isn't any singularity problem. The control law (17) is called NSTMC. Fig. 3 illustrates the phase trajectories of NTSMC [26].

3.2. NTSMC for MU

In MS strategy, the magnitude and the frequency of MU bus voltage should be precisely controlled. In this section the NTSMC is used to design a fast and high performance control for MU bus voltage control.

Consider the following state variables:

$$x_1 = v_f - v_f^*$$

$$x_2 = \dot{x}_1 = c\,(i_f - i_o) - \dot{v}_f^* \tag{18}$$

where v_f^* is the reference voltage vector.

Taking the time derivative of (18) and using (1) and (2), the following state space equations are obtained:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = c\left[\left(a\,(v_i - b i_f - v_f) - \frac{di_o}{dt}\right)\right] - \ddot{v}_f^* = c(av_i + f) - \ddot{v}_f^* \tag{19}$$

where $f = c\left[\left(a\,(-b i_f - v_f) - \frac{di_o}{dt}\right)\right]$ and v_i is the control input.

The NTSMC sliding variable is chosen as:

$$s = x_1 + \beta^{-1} {x_2}^{p/q} \tag{20}$$

Table 1. The parameters of the islanded MG

The nominal (base) power	3 MVA
VSIs nominal voltage	600 V
MG frequency	50 Hz
Line1	0.35+j0.785 Ω
Line2	0.25+j0.625 Ω
Line3	0.1+j0 Ω
VSIs DC voltage	1500 V
Switching frequency	2 kHz
Filter resistance	0.002 Ω
Filter inductance	500 μH
Filter capacitance	400 μF

where $s = [s_\alpha s_\beta]^T$.

Taking the time derivative of (20) and using (19), yields

$$\begin{aligned} \dot{s} &= \dot{x}_1 + \beta^{-1}\frac{p}{q}{x_2}^{\frac{p}{q}-1}\dot{x}_2 \\ &= x_2 + \beta^{-1}\frac{p}{q}{x_2}^{\frac{p}{q}-1}[c(av_i + f) - \ddot{v}_f^*] \end{aligned} \tag{21}$$

Using nominal parameters and equating $\dot{s}$ from (6) to 0, gives

$$v_{ieq} = (-\beta\frac{q}{p}{x_2}^{2-p/q} + \ddot{v}_f^* - \bar{c}\bar{f})/(\overline{ca}) \tag{22}$$

where v_{ieq} is the equivalent control input. The NTSMC law can be written as

$$v_i = v_{ieq} + v_{ireach} \tag{23}$$

where $v_{ireach} = -sgn\,(s)$.

To compare the proposed control with FLC and a modified conventional SMC the following control laws are also introduced:

First, the following sliding variable is defined

$$s = v_f - v_f^* \tag{24}$$

then if v_i is considered as follow, a FLC and a modified conventional SMC are obtained respectively:

$$v_i = v_{ieq} - K_1\dot{s} - K_2 s \tag{25}$$

$$v_i = v_{ieq} - K_1 sgn(s) - K_2 s \tag{26}$$

where K_1 and K_2 are positive constants and

$$v_{ieq} = \bar{b}i_f + v_f + (\bar{c}di_o/dt + \ddot{v}_f^*)/(\overline{ca}) \tag{27}$$

3.3. NTSMC for SUs

Taking the time derivative of active and reactive powers given in (3) and (4) and substituting from (1) and (2), the dynamic equation of active and reactive powers can be written as:

$$\dot{P} = f_P + u_P \tag{28}$$

$$\dot{Q} = f_Q + u_Q \tag{29}$$

where

$$\begin{aligned} f_P &= 1.5c[(i_{f\alpha} - i_{o\alpha})\,i_{f\alpha} + (i_{f\beta} - i_{o\beta})i_{f\beta}] \\ &-1.5a[(bi_{f\alpha} + v_{f\alpha})\,v_{f\alpha} + (bi_{f\beta} + v_{f\beta})v_{f\beta}] \end{aligned} \tag{30}$$

$$u_P = 1.5a(v_\alpha v_{i\alpha} + v_{f\beta}v_{i\beta}) \tag{31}$$

$$\begin{aligned} f_Q &= 1.5c[(i_{f\beta} - i_{o\beta})\,i_{f\alpha} - (i_{f\alpha} - i_{o\alpha})i_{f\beta}] \\ &-1.5a[(bi_{f\alpha} + v_{f\alpha})\,v_{f\beta} - (bi_{f\beta} + v_{f\beta})v_{f\alpha}] \end{aligned} \tag{32}$$

$$u_Q = 1.5a(v_{f\beta}v_{i\alpha} - v_{f\alpha}v_{i\beta}) \tag{33}$$

Consider the following new variables:

$$y_1 = \int (P - P^*)dt \tag{34}$$

$$y_2 = P - P^* \tag{35}$$

$$z_1 = \int (Q - Q^*)dt \tag{36}$$

$$z_2 = Q - Q^* \tag{37}$$

Using the variables defined in (34)-(37), the state space equations can be written as

$$\begin{aligned} \dot{y}_1 &= y_2 \\ \dot{y}_2 &= \dot{P} - \dot{P}^* = f_P + u_P - \dot{P}^* \end{aligned} \tag{38}$$

$$\begin{aligned} \dot{z}_1 &= z_2 \\ \dot{z}_2 &= \dot{Q} - \dot{Q}^* = f_Q + u_Q - \dot{Q}^* \end{aligned} \tag{39}$$

The NTSMC sliding variables are chosen as:

$$s_P = y_1 + \beta^{-1}{y_2}^{p/q} \tag{40}$$

$$s_Q = z_1 + \beta^{-1}{z_2}^{p/q} \tag{41}$$

Taking the time derivative of (40)-(41) and using (38)-(39), yields

$$\begin{aligned} \dot{s_P} &= \dot{y}_1 + \beta^{-1}\frac{p}{q}{y_2}^{\frac{p}{q}-1}\dot{y}_2 \\ &= y_2 + \beta^{-1}\frac{p}{q}{y_2}^{\frac{p}{q}-1}[f_P + u_P - \dot{P}^*] \end{aligned} \tag{42}$$

$$\begin{aligned} \dot{s_Q} &= \dot{z}_1 + \beta^{-1}\frac{p}{q}{z_2}^{\frac{p}{q}-1}\dot{z}_2 \\ &= z_2 + \beta^{-1}\frac{p}{q}{z_2}^{\frac{p}{q}-1}[f_Q + u_Q - \dot{Q}^*] \end{aligned} \tag{43}$$

where u_P and u_Q are the control inputs.

Using nominal parameters and equating $\dot{s}_P$ and $\dot{s}_Q$ from (42) and (43) to 0, gives

$$u_{Peq} = -\beta\frac{q}{p}{y_2}^{2-\frac{p}{q}} - \overline{f}_P + \dot{P}^* \tag{44}$$

$$u_{Qeq} = -\beta\frac{q}{p}{z_2}^{2-\frac{p}{q}} - \overline{f}_Q + \dot{Q}^* \tag{45}$$

where $\overline{f}_P$ and $\overline{f}_Q$ are the nominal values of f_P and f_Q respectively.

The NTSMC laws can be written as

$$u_i = u_{ieq} + u_{ireach} \tag{46}$$

where $i \in \{P, Q\}$ and $u_{ireach} = -sgn\,(s_i)$.

To compare the proposed control with FLC and a modified conventional SMC the following control laws are also introduced:

First, the following sliding variables are defined

$$s_P = P - P^* \tag{47}$$

$$s_Q = Q - Q^* \tag{48}$$

then if u_i is considered as follow, a FLC and a modified conventional SMC are obtained respectively:

$$u_i = u_{ieq} - K_4 s_i \tag{49}$$

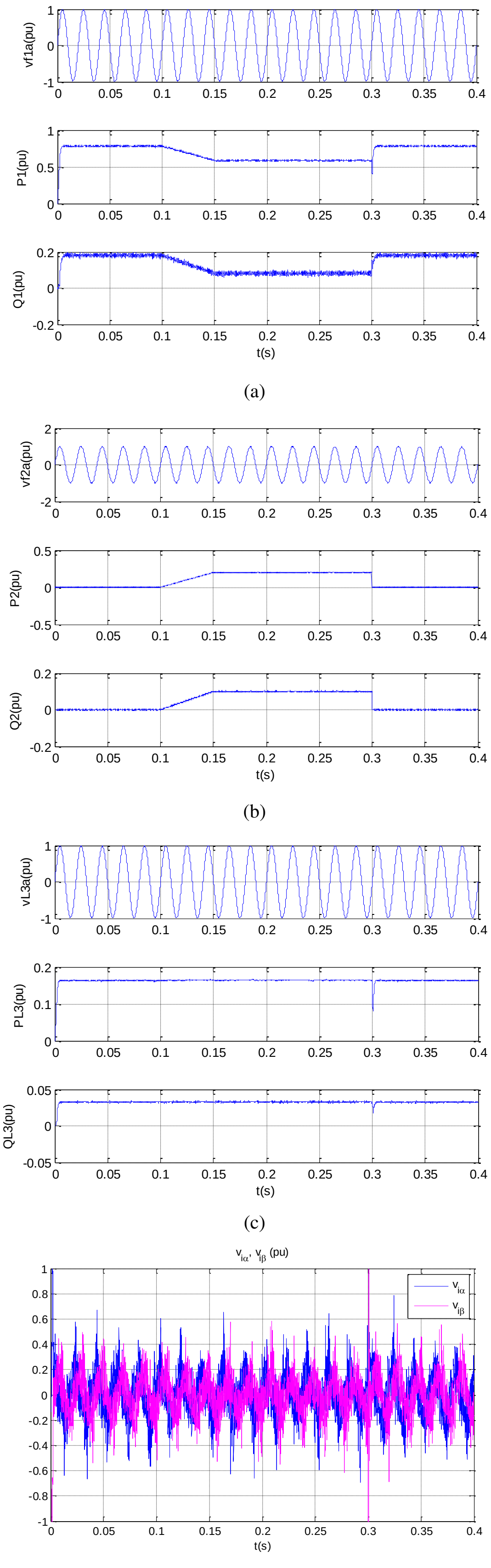
$$u_i = u_{ieq} - K_3 sgn(s_i) - K_4 s_i \tag{50}$$

where $i \in \{P, Q\}$; K_3 and K_4 are positive constants and

$$u_{ieq} = -\overline{f}_i \tag{51}$$

4. SIMULATION RESULTS

To study the capability of the designed NTSMCs for the islanded MGs, the MG given in Fig. 1 is simulated using MATLAB SIMULINK with the parameters in Table 1. The SIMULINK solver is configured as fixed-step with a discrete sample time of 5μs. The MU nominal power and the inverters nominal voltage are used as base values. The MG is examined using the designed controls in several cases.



(a)

(b)

(c)

(d)

Fig. 4. Case 1. NTSMC: voltage, powers of buses and control signals of DG1: (a) PC1, (b) PC2 and (c) Load3 (d) v_i, v_i of DG1

4.1. Case 1

This case is the normal testing conditions for the proposed controls. In this case, from t=0s to t=0.1s, only the MU delivers the demand powers. From t=0.1s to t=0.15s, the active and reactive powers of the SU changes from 0 to 0.2pu and 0.1pu linearly respectively. In Fig. 4, the voltages and powers of three buses (PC1, PC2 and Load3) of this case are shown. In these simulation results, the active and reactive powers track their references perfectly and as the SU powers are increased, the MU powers are decreased. The voltages are sinusoidal with very low harmonics and the MU bus voltage is controlled correctly. At t=0.3s the active and reactive powers of SU set to zero and the MU delivers all of the MG powers. No voltage deviation is detected and the responses are satisfactory without any low frequency oscillations. The voltage THDs are below 2.5% necessary by IEEE 1547 and IEC 61727 standards (50% of the current harmonic limits) [33].

It is worthwhile to note that other control methods for grid connected inverters exist which can result same or even better results than the proposed controls; however most of them have sophisticated control or adaptation laws or a complicated design procedures. In the following, comparisons with FLC and CSMC are presented and those sophisticated controls are out of the scope of the present paper.

4.2. Case 2

In this case, all of the settings are alike to the ones considered in case 1; however, the controllers are FLCs. Fig. 5 represents the simulation results of this case. Compared to the case 1 some oscillations are seen on active and reactive powers of MU and Load3 which are the consequences of the observable increases and decreases in voltages. Actually, using FLC, the MU voltage tracking is not as perfect as the tracking in case 1. In addition, FLC is not a robust control against disturbances and uncertainties.

4.3. Case 3

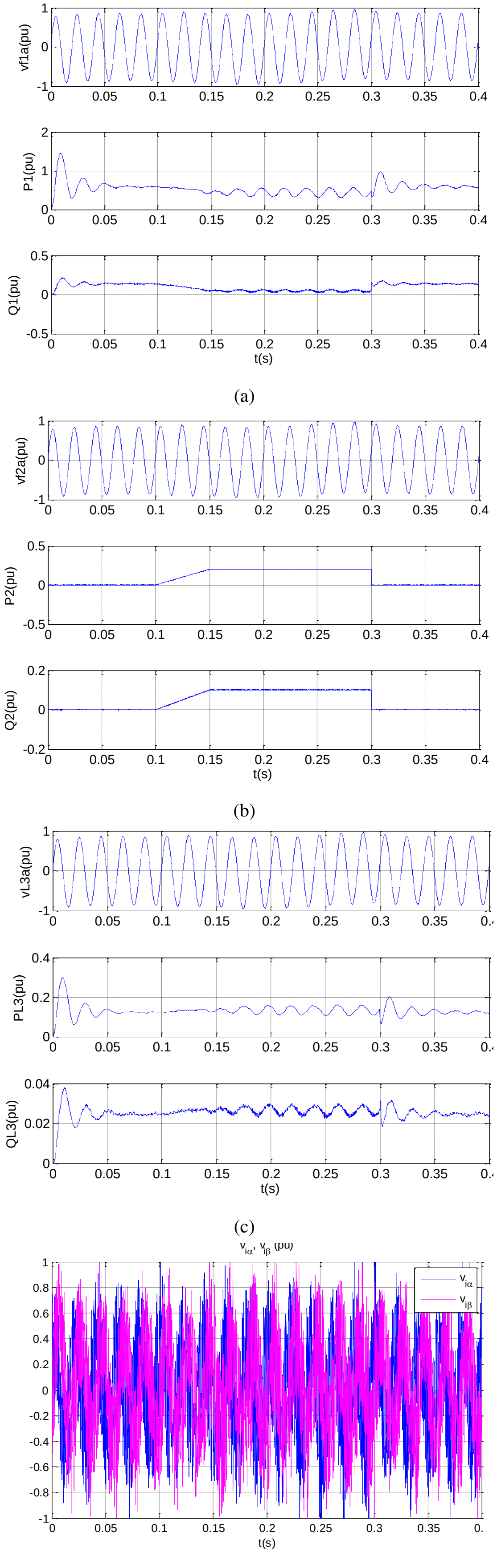
In this case, again all of the settings are alike to the ones considered in case 1; however, the controls are modified CSMCs. Fig. 6 represents the simulation results of this case. The chattering effect and high control efforts are very evident. The voltages and active and reactive powers are affected extremely and contain high frequency contents. VSIs filters cannot remove these high frequency contents. The chattering phenomena can also excite dynamics which are not modeled and causes instability in the real physical system; furthermore, it increases the power loss of VSI.

The control signals of the three controllers are also shown in Figs. 4d, 5d and 6d. These waveforms illustrate the lower control effort of the NTSMC despite the uncertainties in the parameters.

Comparing the above three cases, it results that in the presence of uncertainties in some parameters, only the responses of the proposed control method are acceptable and the FLC method fluctuates and the CSMC method also suffers from the chattering phenomenon. The chattering phenomena can be reduced by replacing the sign function with the saturation function; however, steady state errors will be increased. It is worth noting that in these three cases, the conditions are normal, despite the nonlinear and harmonic loads, the possibility of instability and the appearance of more unfavorable results than the two controls FLC and CSMC is not unexpected. Another thing that can be seen in the results of these three cases is that the power ripple is less by using the proposed method.

4.4. Case 4

The increasing penetration of loads with switching converters increases harmonic distortions in the MGs. This case is completely similar to the case 1; but, a rectifier which is a nonlinear load is paralleled to Load3 at time 0.25s. Fig. 7 illustrates the simulation



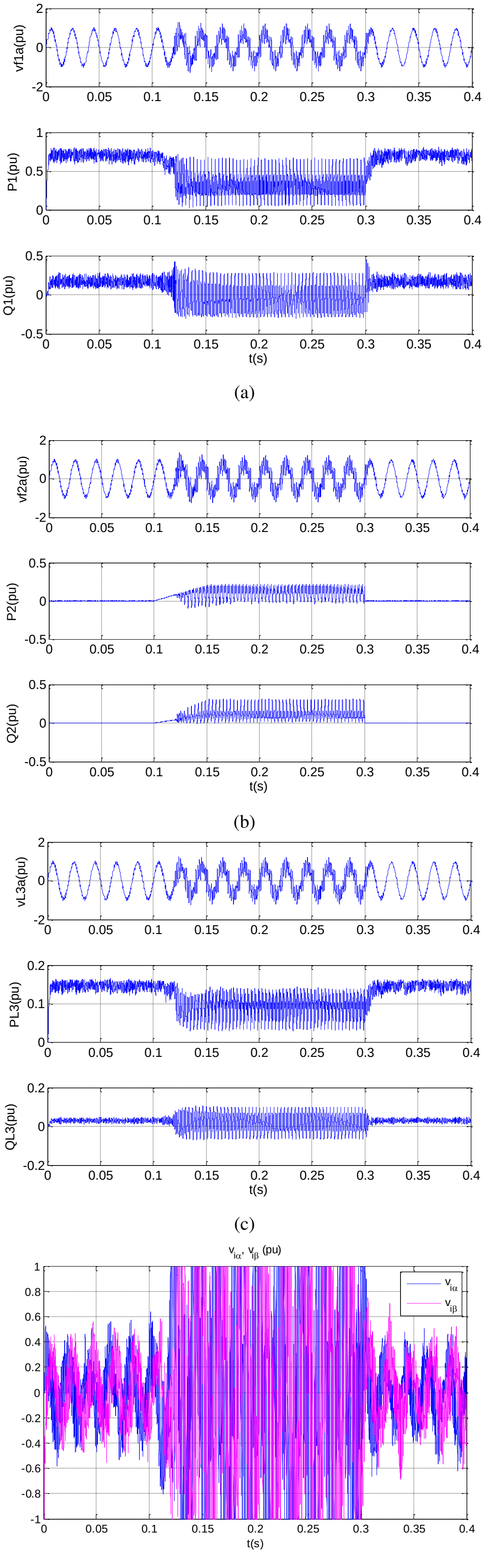
(a)

(b)

(c)

(d)

Fig. 5. Case 2. FLC: voltage, powers of buses and control signals of DG1: (a) PC1, (b) PC2 and (c) Load3 (d) v_i, v_i of DG1



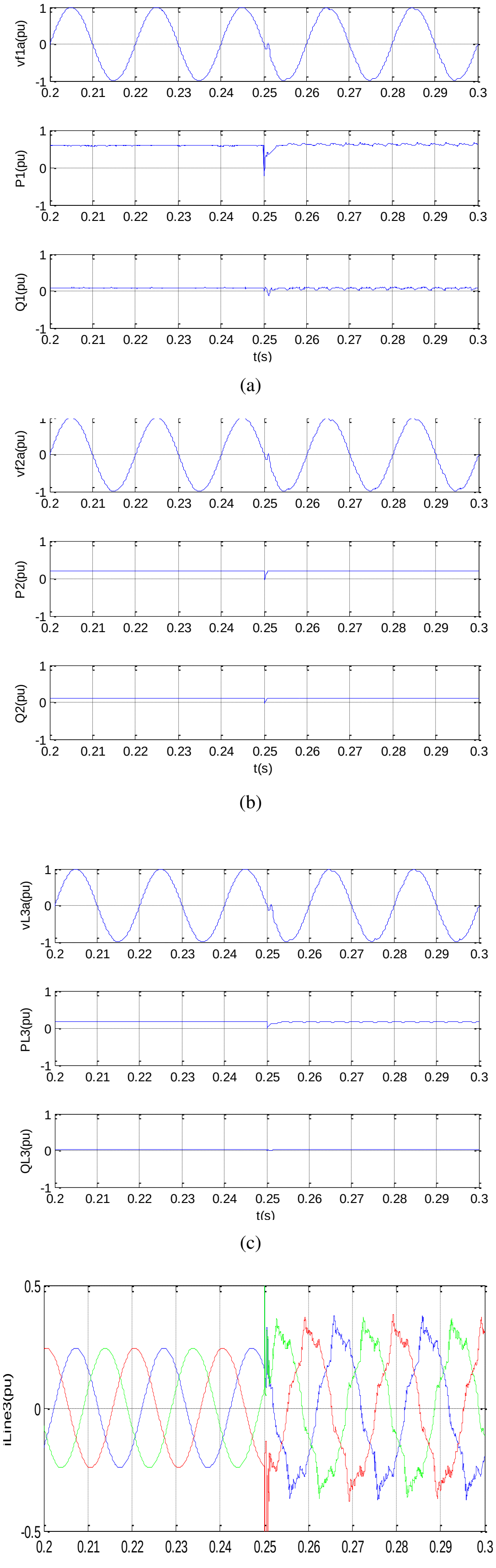
(a)

(b)

(c)

(d)

Fig. 6. Case 3. modified CSMC: voltage, powers of buses and control signals of DG1: (a) PC1, (b) PC2 and (c) Load3 (d)



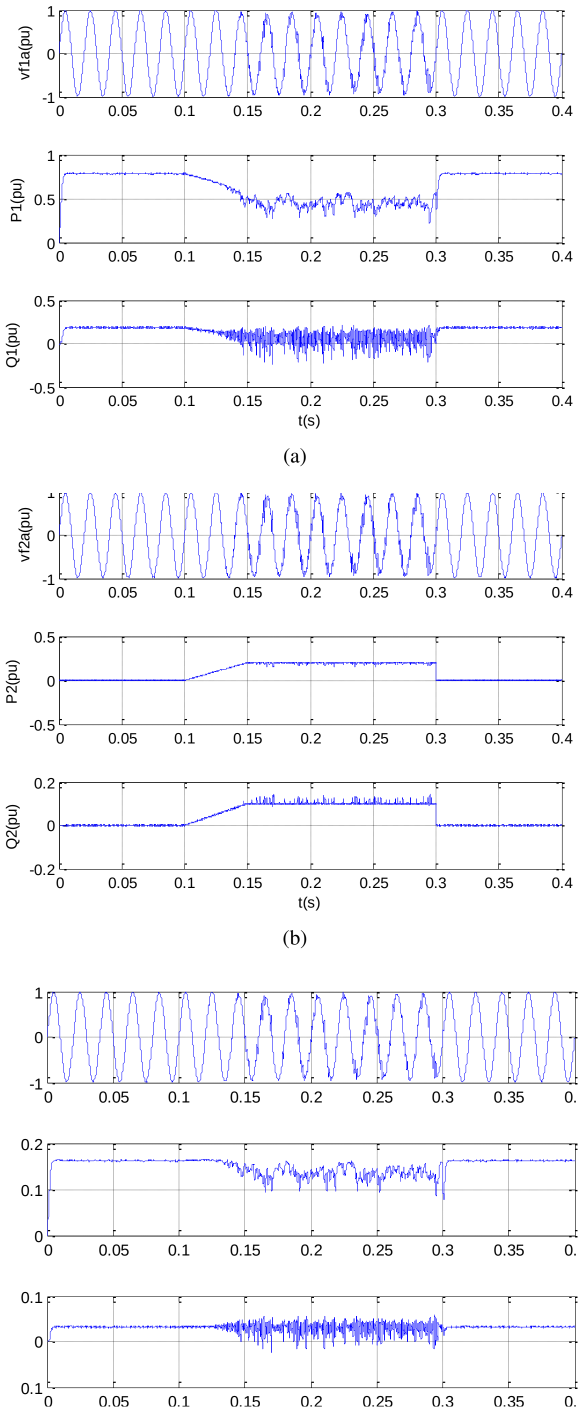
(a)

(b)

(c)

(d)

Fig. 7. Case 4. NTSMC with harmonic load (rectifier): voltage, powers of buses: (a) PC1, (b) PC2 and (c) Load3, (d) currents of the Line3



(a)

(b)

(c)

Fig. 8. Case 5. high impedance lines: voltage, powers of buses: (a) PC1, (b) PC2 and (c) Load3

results of this case. Using the designed NTSMCs, one can see that despite the harmonics in Line3 current, the voltages remain sinusoidal and the demand powers are provided by MU and SU perfectly. Using the NTSMCs, the MG has a smooth and satisfactory operation. The effect of harmonic load on voltages and powers is negligible which is the result of the designed high performance controls. This case also represents the robustness of the proposed NTSMCs.

4.5. Case 5

This case is completely similar to the case 1; but, very higher impedances are considered for Line1 and Line2: (0.35+j0.785)*6 Ω and (0.25+j0.625)*6 Ω. Fig. 8 shows the simulation results of this case. The simulation results illustrate that the MG becomes unstable; because the MU can't control the voltages of the distant buses with high impedances. This test represents that MS strategy is perfect for islanded MGs in which the impedances of the lines are not very high or the power electronics systems with paralleled VSIs.

5. CONCLUSIONS

MGs are becoming popular in delivering electrical power to local loads. Two NTSMCs are designed for islanded MGs with inverter based DGs. MS strategy is adopted to control the voltage and delivered powers. Simulation results are presented for an islanded MG with two DGs; however, the proposed controls can be used for any islanded inverter-based MG with any number of DGs. A comparison of three controls (NTSMC, FLC and a modified CSMC) are presented. The simulation results illustrate the advantages of the proposed NTSMCs. The MU bus voltage and the delivered powers of the SU are controlled perfectly. By changing the loads or the active and reactive power references of the SU, the remaining load demand is provided by the MU and a decent load sharing between VSIs is achieved. Using the designed NTSMC scheme, during the transients, almost no overvoltage or undervoltage is observed and a perfect and reliable control is achieved. In addition, the volatility inherent to the DGs is simulated which shows the DGs can inject their power when available. The merits of the proposed control scheme are: rather simple configuration of controllers for implementation, perfect tracking and robustness of the NSTSMCs. The proposed NTSMCs can be employed in parallel inverters to control the voltage or the powers and can be compared with new adaptive model-free control techniques in future works.

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