IJARIIT INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

ISSN: 2454-132X
Impact factor: 4.295
(Volume 4, Issue 4)
Available online at: www.ijariit.com

Virtual synchronous generator control with ANFIS controller for parallel inverters in micro grids

P. Yaswanth Kumar Reddy
yaswanthk09@gmail.com
Sri Venkateswara College of Engineering, Chittoor, Andhra Pradesh

S. Ravichandran
stravichandran@gmail.com
Sri Venkateswara College of Engineering, Chittoor, Andhra Pradesh

ABSTRACT

Virtual synchronous generator (VSG) control is a promising correspondence less control strategy in a micro grid for its inertia support highlight. Be that as it may, active power wavering also, despicable transient active power sharing are watched when fundamental VSG control is connected. Also, the issue of receptive control sharing mistake, acquired from routine hang control, ought to likewise be routed to acquire attractive stable state execution. In this paper, an upgraded VSG control is proposed, with which swaying damping and legitimate transient active power sharing are accomplished by changing the virtual stator reactance in light of state-space examinations. Besides, correspondence less precise receptive power-sharing is accomplished in view of inversed voltage droop control include (V–Q droop control) and normal ac bus voltage estimation. Simulation confirms the change presented by the proposed upgraded VSG control procedure.

Keywords— *DC-AC power converters, Distributed power generation, Droop control, Micro grids, Power control, Power system dynamics, Power system modeling, Reactive power control, State-space methods, Virtual synchronous generator*

1. INTRODUCTION

Late years, inverter-interfaced distributed generators (DGs) with renewable energy sources (RES), e.g., photovoltaic and wind turbines, have been created to understand energy emergency and natural issues. To encourage the coordination of DGs in the distribution framework, the idea of the micro grid is proposed [1]. The control procedures of micro grids are favored to be in a correspondence less way as a result of its decentralized element. In spite of the fact that in a various leveled micro grid control structure, correspondence is required for the auxiliary, what's more, tertiary control, it is still prescribed to understand the fundamental elements of a micro grid in the essential control level without correspondence [2], [3]. Droop control is a generally received correspondence less control technique in a micro grid. By dropping the frequency against the active power (P–ω hang) and the yield voltage against reactive power (Q–V hang), stack sharing between DGs can be performed in an autonomic way, which is like the power-sharing between parallel synchronous generators (SGs) [4], [5]. In a few references [6]–[8], it is suggested that P–V and Q–ω droop controls are more appropriate for low voltage (LV) micro grid in the light of the resistive line impedance include. In the interim, the P–ω and Q–V hang controls are still substantial in LV micro grid by including inductive virtual impedance [2], [3], [9].

In any case, as the majority of DG control strategies, a routine droop control gives barely any inertia support to the micro grid, therefore a droop control-based micro grid is more often than not inertia less and delicate to blame. To give inertia support for the framework, control techniques to imitate virtual inertia are proposed in late writings, for example, virtual synchronous generator (VSG) [10]-[11], virtual synchronous machine, what's more, synchro converter In spite of the fact that their name and control conspire to vary from each other, the standards are comparable in the viewpoint that every one of them copy the transient qualities of SG by copying its essential swing condition. For less complex elucidation, these techniques are called VSG control in this paper. An exhaustive overview on VSGs and the current topologies addition, a one of a kind technique to give virtual inertia by altering the droop coefficient in droop control. To share the load in parallel operation, droop attributes are additionally copied in some VSG control plans [12], For this situation, VSG control acquires the benefits of droop control, and outperforms the last in terms of transient frequency stability attributable to its lower df/dt rate. Thusly, VSG control can be considered as a potential update for the correspondence less control strategy for a micro grid.

Nonetheless, when VSG control is connected in micro grids, a few issues have been seen, for example, oscillation in active power during an unsettling influence, wrong transient active power sharing during stacking move and errors in reactive power sharing.

Active power oscillation during an aggravation is presented by the notable component of the swing condition; hence it is an intrinsic component for a genuine SG and additionally a VSG. It is not a basic issue for SGs since they normally have extensive over-burden capacities, yet the over-burden abilities of inverter-interfaced DGs are not sufficiently high to ride despite the fact that an expansive oscillation. Be that as it may, this swaying can be damped by legitimately expanding the damping proportion or utilizing exchanging inertia. Utilizing smaller inertia may likewise prompt to diminished oscillation; notwithstanding, it is most certainly not supported in light of the fact that giving a lot of virtual inertia is a favorable position that recognizes VSG from other control techniques.

In this paper, a novel strategy for oscillation damping is proposed in light of expanding the virtual stator reactance. Because of the oscillatory component of VSG, wrong transient active power sharing during stacking transition may likewise cause oscillation, which is avoidable if the swing condition what's more, output impedance legitimately, as it is broke down in this paper. Sharing transient loads between SG furthermore, DG is tended, yet hypothetical examination is most certainly not given.

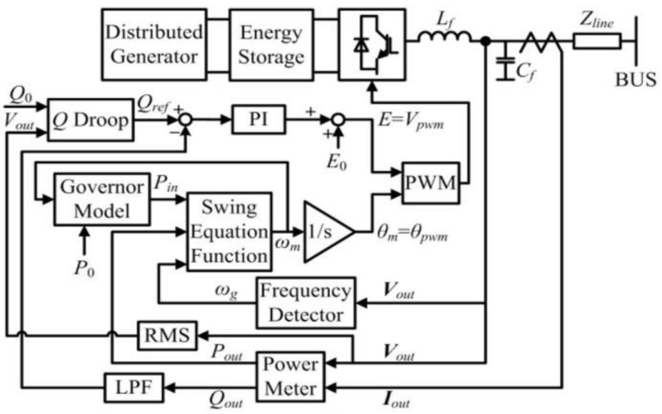
2. BASIC VSG CONTROL SCHEME

Figure 1 demonstrates the structure of a DG utilizing the fundamental VSG control [14]. The primary source of the DG could be photovoltaic panels, power devices, a gas engine or other distributed energy resources (DERs). The energy storage is designed for emulating the kinetic energy stored in rotating mass of an SG, in a request to supply or retain deficient/surplus power created by the essential source in the transient state [13]. As this paper concentrates on the control plan of the inverter, the outline and control of the primary source and energy storage are past the extent of this paper. In the block "Swing Equation Function" in figure 1(a), ω_m is tackled from the swing condition (1) by an iterative technique.

$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dx} + D(\omega_m - \omega_g) \qquad (1)$$

The block “Governor Model" in figure 1 (a) is a ω–P droop controller as appeared in figure 1 (b). In some past, ponders [12]–[14], a first request slack unit is utilized to imitate the mechanical delay in the governor of a real SG. Notwithstanding, in this paper, this postponement is evacuated, because it degrades the dynamic execution of DG.

The block "Q Droop" in figure 1(a) is a V–Q droop controller as appeared in figure 1(c), which contrasts from the routine Q–V droop controller in the reversed input and output. It is essential that inner current or voltage circle is not received in this control conspire, keeping in mind the end goal to make the channel inductor Lf add to the yield impedance and be considered as the stator inductance of the VSG. This stator inductance brings about more inductive output impedance, which is particularly imperative for active and reactive power decoupling in a low voltage micro grid in which line resistance is predominant.



(a)

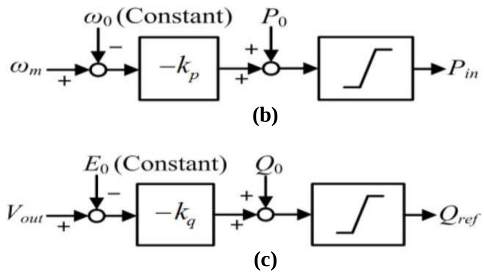


Fig. 1: Block diagram (a) Basic VSG control, (b) “Governor Model” block and (c) “Q Droop” block

By and by, the output voltage is still controlled in a roundabout way by the V–Q droop controller and the PI controller of reactive power. With a specific end goal to reduce the impact of ripples in measured output control, a 20Hz first order low-pass filter is connected for Q_{out} as appeared in figure 1(a). As the output current is measured after the LC channel organize, the reactive power expended by the LC filter is excluded in Q_{out}. Along these lines, no particular inertial process is required for the reactive power PI controller. In a micro grid, with a specific end goal to share the active and reactive power as indicated by the evaluations of DGs without correspondence,

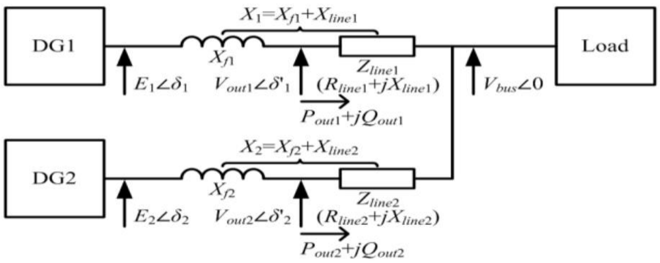


Fig. 2: Structure of a micro grid in islanded mode

$k_p^* = (k_p\omega_o)/S_{base}$, $k_q^* = (k_qE_o)/S_{base}$, $P_o^* = P_o/S_{base}$ and $Q_o^* = Q_o/S_{base}$ ought to be designed similarly for every DG in default [2]. In this paper, to disentangle the elucidation for the instance of various power evaluations, per unit qualities are computed in light of particular power evaluations of DGs.

3. ANALYSES OF TRANSIENT ACTIVE POWER PERFORMANCE

Closed-Loop State-Space Model

In the present work, an islanded micro grid which comprises two DGs utilizing VSG control is contemplated, as it appears in figure 2. The DGs are associated with a typical ac bus through a distribution line, to supply the loads in the micro grid. Take note of that the capacitor of the DG output LC filter in figure 1 is neglected, as its susceptance is generally irrelevant at the fundamental frequency. So as to comprehend the reasons of active power oscillation also, to discover appropriate arrangements, a state-space model for the closed-loop active power control of the micro grid appeared in figure 2 can be obtained as given in (2)–(9). To streamline the model furthermore, concentrate on the particular Eigen values bringing about oscillation, the reactive power part is excluded in this model and the line resistance is disregarded in the inductive output impedance purpose of see. These re-arrangements don't influence the accuracy of the model.

$$\begin{cases} \dot{x} = Ax + Bw \\ y = Cx + Dw \end{cases} \qquad (2)$$

$$w = [\Delta P_{load} \Delta P_{0\_1} \Delta P_{0\_2}]^T \qquad (3)$$

$$y = [\Delta w_{m1} \Delta w_{m2} \Delta P_{0ut1} \Delta P_{0ut2}]^T \qquad (4)$$

$$x = \begin{bmatrix} \Delta w_{m1} + \frac{D_1}{J_1 w_0 (K_1+K_2)} \Delta P_{load} \\ \Delta w_{m2} + \frac{D_2}{J_2 w_0 (K_1+K_2)} \Delta P_{load} \\ \Delta \delta_1 - \frac{1}{K_1+K_2} \Delta P_{load} \end{bmatrix} \quad (5)$$

4. IMPROVEMENT OF REACTIVE POWER SHARING

Figure 3 demonstrates the standards of ω–P and V–Q droop controls in the "Representative Model" and "Q Droop" pieces appeared in figure 1 for the instance of Sbase1: Sbase2 = 2 : 1. As examined in Section 2, k_p^*, k_q^*, P_o^* and Q_o^* are composed similarly. Based on the predefined linear droop characteristic, the wanted power sharing Pin1: Pin2 = 2: 1 can be gotten because the governor input is, ω_m and $\omega_{m1} = \omega_{m2}$ is guaranteed in steady state.

Taking after a similar rule, to share the reactive power as per the power rating proportion, an equivalent voltage reference is required. Be that as it may, for the V–Q droop in essential VSG control appeared in figure 1(c), the voltage reference is the inverter output voltage, which might be an alternate an incentive for every DG even in steady state because of the line voltage drop. As a large portion of past studies depend on Q–V droop, in which the output voltage$V_{out\,i}$. Ought to be controlled in light of measured responsive power $Q_{out\,i}$, the fundamental thought to deliver this issue is to level $V_{out\,i}$ by balancing the output impedance, or to adjust the line voltage drop. Both techniques require awesome exertion in configuration process and complex calculations in DG control law, though came about reactive power sharing is still affected by active power sharing.

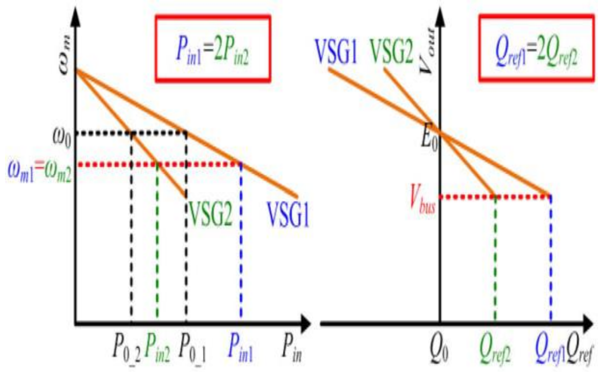


Fig. 3: Principles of *ω–P* and *V–Q* droop control

As the voltage does not require to be controlled straight forwardly in a V–Q droop control plot appeared in figure 1(a), the reference voltage can be picked other than the inverter output voltage. On the off chance that the normal ac bus voltage$V_{bus\,i}$., utilized rather than inverter output voltage$V_{out\,i}$., measure up to reactive power reference esteem $Q_{ref\,1} = Q_{ref\,2}$ can be ensured, as it is delineated in figure 3. In this manner, exact reactive power sharing $Q_{out\,1} = Q_{out\,2}$ ought to be gotten through the utilizing of reactive power PI controller. Also, not at all like output voltage, bus voltage is not impacted by line voltage drop, which is dictated by both active and reactive power. In this manner, reactive power sharing as per the bus voltage is autonomous from active power.

Direct bus voltage estimation is proposed. In any case, in the field applications, it is hard to gauge$V_{bus\,i}$. Specifically, as DGs may be introduced far from the normal ac bus, and the use of correspondence is not favored for dependability reason.

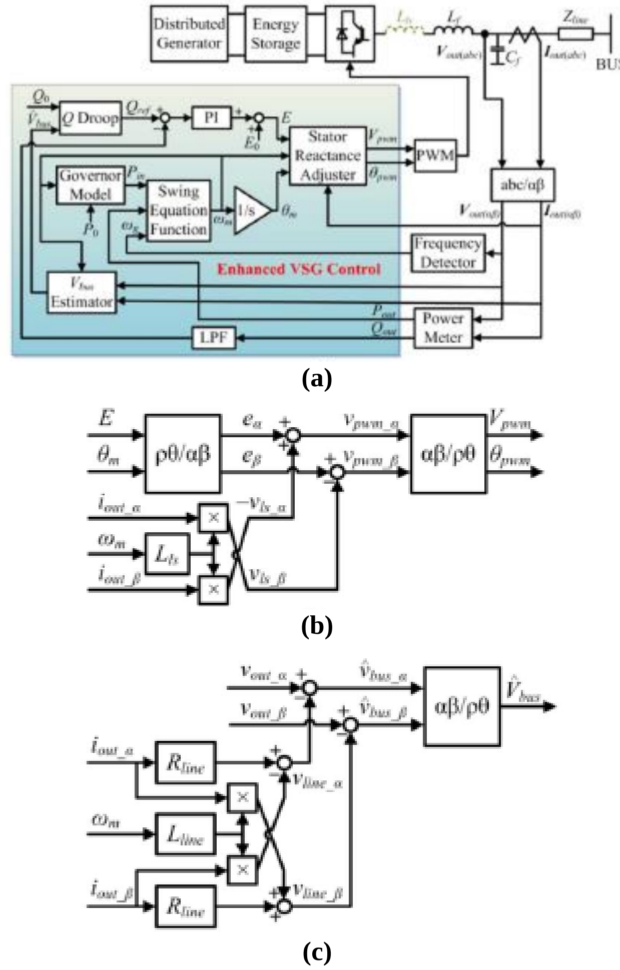


Fig. 4: Block diagram (a) Proposed enhanced VSG control, (b) "Stator Reactance Adjuster" block and (c) "V_{bus} Estimator" block.

5. PROPOSED ENHANCED VSG CONTROL SCHEME

The proposed improved VSG control plan appears in figure 4. Contrasted with the essential VSG control, two noteworthy changes are made, i.e., the stator reactance adjuster and the bus voltage estimator, as appeared in figures 4(b) and 4(c), individually. The capacity of the stator reactance adjuster is to change the output reactance of the DG freely. It is working as a virtual impedance controller. The virtual stator inductor is figured it out by increasing the output current by the virtual stator inductor in the stationary casing. It will be more exactness if inductor current through L_f is utilized. Be that as it may, this builds the quantity of current sensors, which is redundant. As the current flowing into C_f at fundamental frequency is not as much as few percent of the inductor current, utilizing output current rather than inductor current does not influence the execution of the control plot. Tuning of virtual stator inductor $L_{ls\,i}$ is recommended to set aggregate output reactance X_i^* for both DGs in same substantial per unit esteem. The objective esteem is proposed to be *0.7 p.u* since it is a run of the mill an incentive add up to direct-axis transient reactance X_d' of a genuine SG.

$$X_i^2 = \frac{S_{base\,i}\omega_{m\,i}(L_{ls\,i}+L_f+L_{line\,i})}{E_0^2} = 0.7\,p.u \quad (6)$$

The $L_{f\,i}$ and $Z_{line\,i}(R_{line\,i} + jL_{line\,i})$ are considered as known parameters in this paper. As the size of microgrid is for the most part little, the $L_{line\,i}$ distance is effortlessly to be measured or encouraged by the organizer. Regardless of the possibility that it is not the situation, a few online estimations then again keen tuning strategies for $Z_{line\,i}$Zline.

With the proposed outline of stator reactance alteration, oscillation in a VSG-control-based micro grid ought to be practically dispensed with amid a loading transition in islanded mode. Especially, the transition from the grid- associated mode to islanded mode can likewise be considered as a loading transition; along these lines, the oscillation during an islanding occasion ought to likewise be disposed of with the proposed control system, as it is demonstrated by simulation results next area.

The rule of bus voltage estimator in figure 4(c) is comparable to that of stator reactance adjuster in figure 4(b). By ascertaining the line voltage drop in stationary casing utilizing measured output current and line impedance information, the bus voltage can be accessed from the distinction of output voltage furthermore, computed line voltage drop. Since the RMS estimation of evaluated bus voltage $\widehat{V}_{bus}$ for every DG ought to be around break even with, as it is examined in last segment, precise reactive power sharing can be acquired by utilizing evaluated bus voltages as the input references of "Q Droop" rather than particular output voltages of DGs. In spite of the fact that the rule of exhibited bus voltage estimator is not new, utilizing this estimator to acknowledge correspondence less precise reactive power sharing can be considered as a commitment in the introduce work.

$$\text{Assuming } \widehat{V}_{bus1}^{*} = V_{bus}^{*} + \Delta\widehat{V}_{1}^{*}, \widehat{V}_{bus2}^{*} = V_{bus}^{*} + \Delta\widehat{V}_{2}^{*},$$
$$Q_{out1}^{*} - Q_{out2}^{*} = -k_{q}^{*}\left(\Delta\widehat{V}_{1}^{*} - \Delta\widehat{V}_{2}^{*}\right) \quad (12)$$

That is to state, the reactive power sharing mistake brought on by estimation mistakes is dictated by the V–Q droop gain k_q^*. The outline of k_q^* is an outstanding exchange off between voltage deviation and reactive power control exactness. Considering the plausible ripples in the deliberate RMS estimation of $\widehat{V}_{bus}$, k_q^* is prescribed to be 5 pu for the present illustration. It ought to be called attention to that the expanded output reactance by including the virtual stator inductor Ls causes a reduction in the reactive control plant gain, as appeared in figure 5.

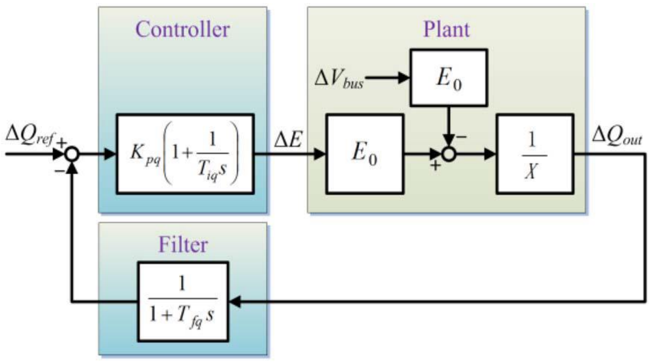


Fig. 5: Small-signal model of reactive power control loop

An adaptive Neuro-fuzzy inference system

An adaptive Neuro-fuzzy derivation framework or versatile system based fuzzy deduction framework (ANFIS) is a sort of counterfeit neural system that depends on the Takagi–Sugeno fuzzy induction framework. The strategy was produced in the mid-1990s. Since it coordinates both neural systems and fuzzy rationale standards, it can possibly catch the advantages of both in a solitary structure. Its induction framework compares to an arrangement of fuzzy IF-THEN decides that have learning capacity to inexact nonlinear capacities. Thus, ANFIS is thought to be an all-inclusive estimator. For utilizing the ANFIS as a part of a more productive and ideal way, one can utilize the best parameters acquired by hereditary calculation. ANFIS: Artificial Neuro-Fuzzy Inference Systems

- ANFIS is a class of adaptive networks that are functionally equivalent to fuzzy inference systems.
- ANFIS represent Sugeno e Tsukamoto fuzzy models.
- ANFIS uses a hybrid learning algorithm.

In the field of artificial intelligence, neuro-fuzzy alludes to mixes of fake neural systems and fuzzy rationale. Neuro-fuzzy hybridization brings about a half and half astute framework that synergizes these two procedures by joining the human-like thinking style of fuzzy frameworks with the learning and connectionist structure of neural systems. Neuro-fuzzy hybridization is generally named as Fuzzy Neural Network (FNN) or Neuro-Fuzzy System (NFS) in the writing. Neuro-fuzzy framework (the more mainstream term is utilized from this time forward) fuses the human-like thinking style of fuzzy frameworks using fuzzy sets and a semantic model comprising of an arrangement of IF-THEN fuzzy standards. The primary quality of neuro-fuzzy frameworks is that they are widespread approximates with the capacity to request interpretable IF-THEN principles.

The quality of neuro-fuzzy frameworks includes two conflicting necessities in fuzzy displaying: interpretability versus exactness. Practically speaking, one of the two properties wins. The neuro-fuzzy in fuzzy demonstrating research field is separated into two zones: semantic fuzzy displaying that is centered on interpretability, for the most part, the Mamdani model; and exact fuzzy demonstrating that is centered on exactness, primarily the Takagi-Sugeno-Kang (TSK) model.

Representing fuzzification, fuzzy inference, and defuzzification through multi-layers feed-forward connectionist networks. It must be pointed out that interpretability of the Mamdani-type neuro-fuzzy systems can be lost. To improve the interpretability of neuro-fuzzy systems, certain measures must be taken, wherein important aspects of interpretability of neuro-fuzzy systems are also discussed.

A recent research line addresses the data_stream_mining case, where neuro-fuzzy systems are sequentially updated with new incoming samples on demand and on-the-fly. Thereby, system updates do not only include a recursive adaptation of model parameters, but also a dynamic evolution and pruning of model in order to handle concept drift and dynamically changing system behavior adequately and to keep the systems/models "up-to-date" anytime.

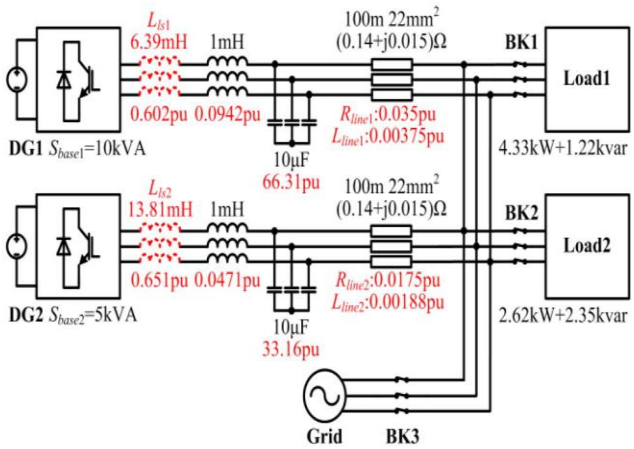


Fig. 6: Simulation circuit

6. SIMULATION RESULTS

Simulations are executed in PSCAD/EMTDC condition to confirm the viability of the proposed improved VSG control plot. A micro grid appeared in figure 6 is examined. As it appears in figure 6, impedances of output filters and lines of every DG vary in per unit values. The sequence of simulation appears in Table 2. Occasions of islanding from grid, loading transition, what's more, and purposeful active power sharing change are simulated at 21 s, 24 s, and 27 s, individually. The simulation results appear in figure 7.

As it is delineated in figure 7(a), when the micro grid is islanded at 21 s, and when load 2 is associated at 24 s, oscillation can be seen in active power when the essential VSG control is connected for both DGs. This oscillation is nearly eliminated by applying the proposed improved VSG control appeared in figure 7(b). As the disturbance at 27 s is brought on by the change of active power set estimation of DG1, which is most certainly not a loading transition, active power oscillation can't be dispensed with for this situation. In any case, the proposed upgraded VSG control expands the damping proportion; accordingly, the overshoots in figure 7(b) are littler than that in figure 7(a). In the interim, the oscillation periods turn out to be longer, on the grounds that the damped common frequencies are decreased. Take note of that the rate of change of frequency continues as before in all cases, which recommends that the proposed upgraded VSG control has no impact on the inertia support highlight of VSG control.

Table 1: Simulation Parameters

Parameter	Value	Parameter	Value
Common Parameters			
S_{base1}	10 kVA	M_i^*	8 s
S_{base2}	5 kVA	D_i^*	17 pu
$E_0 = V_{grid}$	200 V	$k_{p\,i}^*$	20 pu
$w_0 = w_{grid}$	376.99 rad/s	$k_{q\,i}^*$	5 pu
$P_{0\,i}^*$	1 pu	$T_{f\,q\,i}$	7.96 X 10^{-3} s
$Q_{0\,i}^*$	0 pu		
Basic VSG control			
$K_{pq\,i}^*$	0.0025 pu	$T_{iq\,i}$	1.25 X 10^{-4} s
Enhanced VSG control			
$K_{pq\,i}^*$	0.0125 pu	$T_{iq\,i}$	1.25 X 10^{-4} s

Table 2: Simulation sequence

Times	Grid	$P_{0\_1}^*$	$P_{0\_2}^*$	Load
t< 21 s	Connected	1 pu	1 pu	Load 1
21s ≤ t< 24s	Disconnected	-	-	-
24s ≤ t< 27s	-	-	-	Load 1+2
27s ≤ t< 30s	-	-	0.6 pu	-

In addition, on account of the fundamental VSG control, reactive power is not shared appropriately in islanded mode and is most certainly not controlled at set an incentive in the grid-associated mode, because of the voltage drop through the line impedance, as appeared in figure 7(a). Also, reactive power control is not autonomous from active power control, as a change of set estimation of active power at 27 s additionally causes a change of reactive power sharing. These issues are altogether illuminated in the upgraded VSG control, as it appears in figure 7(b). It is additionally important that the steady-state deviations of DG voltage and bus voltage get to be distinctly littler when the upgraded VSG control is connected.
Simulations are executed in an islanding micro grid, of which the circuit is the same as that of simulation shown in figure 7, except that instead of dc sources, ac supply rectified by diode bridges is used to imitate the dc output of DGs, and the breaker BK3 is opened and Simulation sequence is shown in Table 3. Control Parameters are the same as those listed in Table 2, and the Simulation results are shown in figure 8.

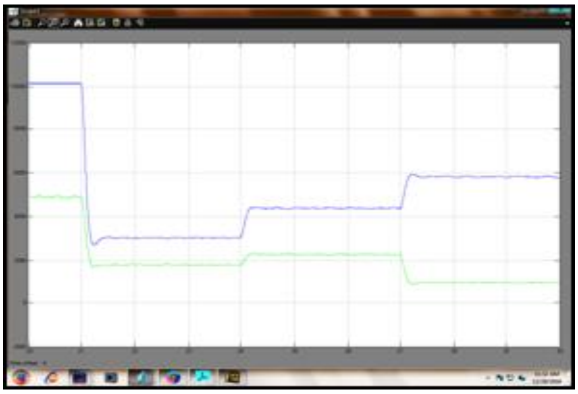
Table 3: Simulation Sequence

Times	$P_{0\_1}^*$	$P_{0\_2}^*$	Load
t< 0.5 s	1 pu	1 pu	Load 1
0.5s ≤ t< 3s	-	-	Load 1+2
3s ≤ t< 5s	-	0.6 pu	-

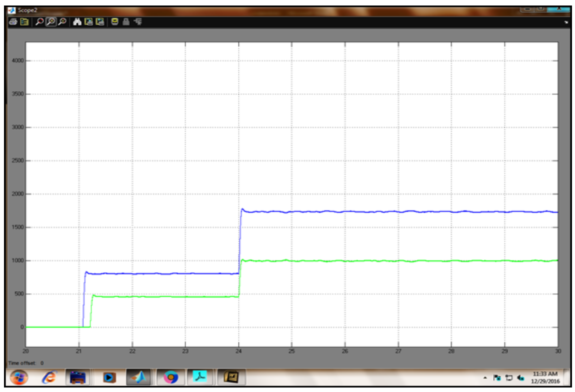
Simulation results verify again the effectiveness of the proposed enhanced VSG control. First, the oscillation due to loading transition at 0.5 s is eliminated, and the oscillation due to the change of the set value of active power at 3.0 s is damped. It implies that the proposed enhanced VSG control is able to track the loading transition rapidly and accurately without oscillation; meanwhile, the inertia support of the basic VSG control is kept. Even when an oscillation occurs, the overshoot is suppressed owing to increased system damping.

Furthermore, by applying the enhanced VSG control, reactive power is shared according to power rating ratio and is immune to active power sharing change and line impedance mismatch in per unit values. Although ripples in the RMS value of output voltage can be observed due to a slight load unbalance, the reactive power is controlled well when the enhanced VSG control is applied.

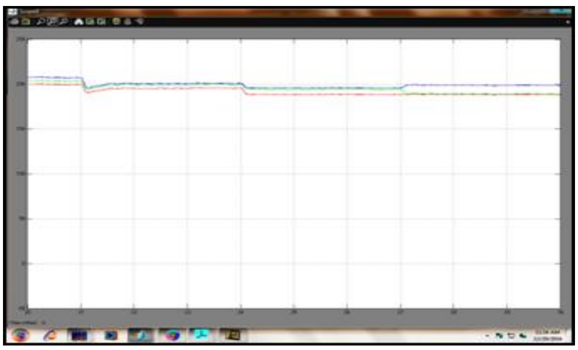
6.1 Simulation results of proposed method



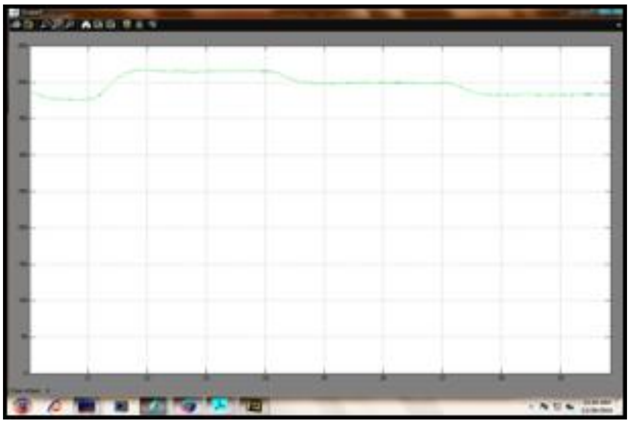
Active and reactive powers of load1



Active and reactive powers of load 2



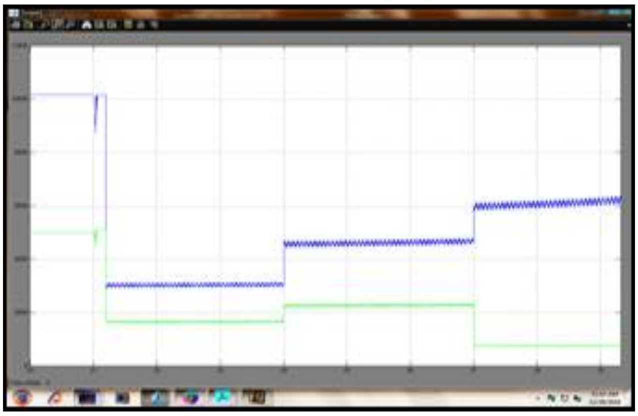
Voltage magnitudes



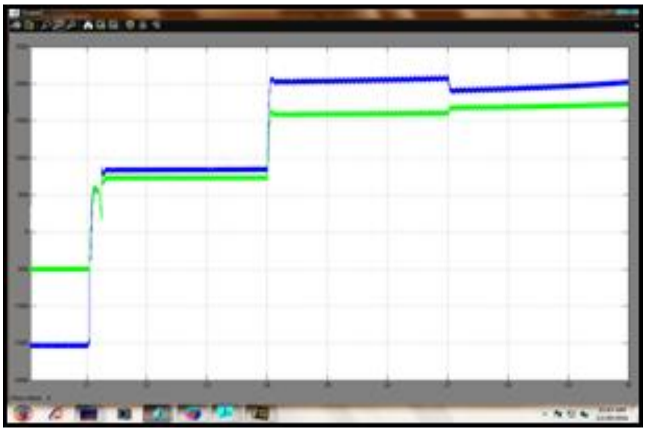
Frequencies

Fig. 7(a): Simulation results of active power, reactive power, voltage and frequency when both DGs are controlled by the proposed method of VSG control

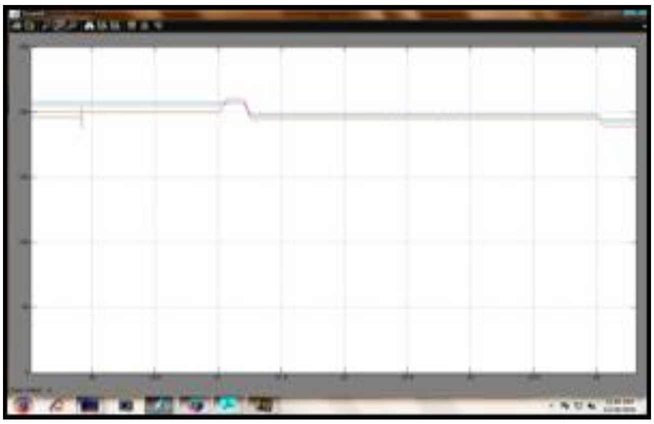
6.2 Simulation results for conventional method



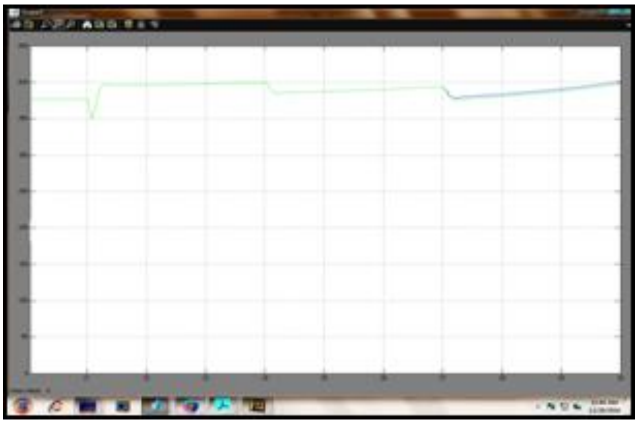
Active and reactive powers of load1



Active and reactive powers of load2



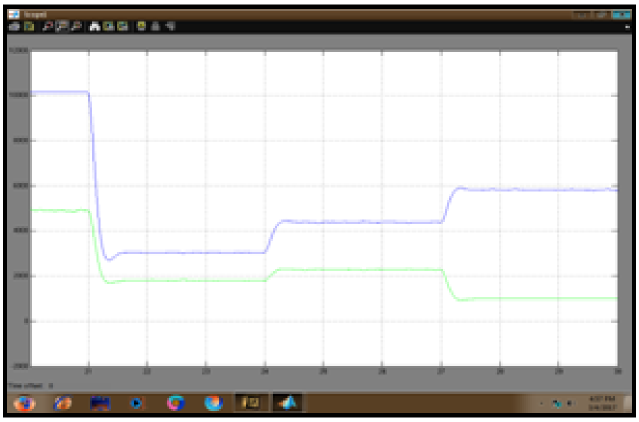
Voltage magnitudes



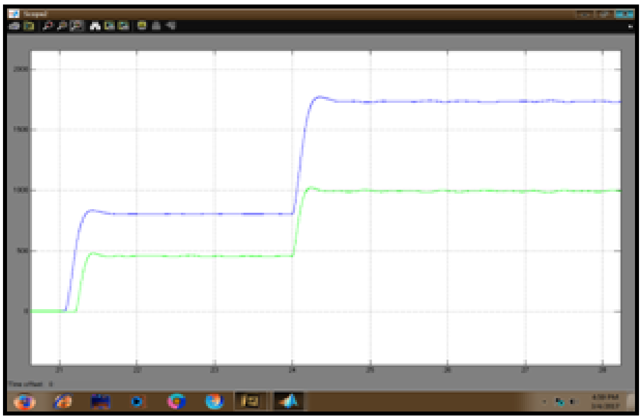
Frequencies

Fig. 8: Simulation results for conventional method

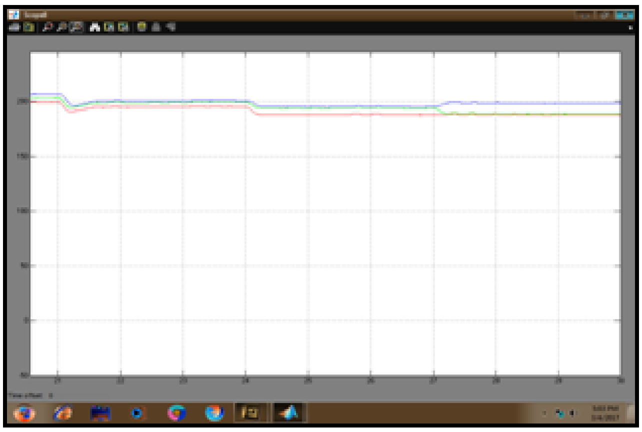
6.3 Simulation results for extension method with ANFIS controller



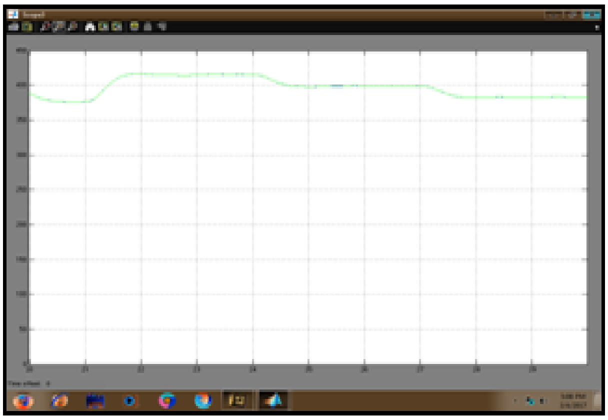
Active and reactive powers of load1



Active and reactive powers of load2



Voltage magnitudes



Frequencies

Fig. 8: Extension method results of active power, reactive power, voltage and frequency when both DGs are controlled by ANFIS controller

7. CONCLUSION

In this paper, an upgraded VSG control is proposed as a novel correspondence less control technique in a micro grid. A stator reactance adjuster is produced in view of state-space analyses, in order to increase the active power damping and to appropriately share transient active power. A novel communication less reactive power control methodology in view of inversed voltage droop control (V–Q droop control) and regular ac bus voltage estimation is likewise proposed to accomplish exact reactive power sharing, which is resistant to active power sharing change also, line impedance mismatch. Simulation comes about showed that the proposed upgraded VSG control accomplishes desirable transient and steady-state exhibitions, and keeps the inertia support highlight of VSG control. Subsequently, the proposed upgraded VSG control is an ideal decision for the control arrangement of DGs in micro grids.

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