Improvement Reactive Power Sharing In Inverter-Based Microgrids

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Abstract-*This paper studies the distributed reactive power sharing problem for microgrids with connected Ac inverters. For microgrids in the islanded process, due to the effects of unequal line impedance, the reactive power could not be shared exactly with the conservative sag method. In the addition of microgrids, distributed generation units include microturbines, photovoltaic (PV) sets, fuel cells, wind energy systems, The goal is to enable renewable power sources connected to the point of common coupling (PCC) through three-phase three-wire six inverters to cooperatively feed linear and non-linear local loads. By the Lyapunov approach, a novel distributed voltage controller with nonlinear state feedback is suggested for reactive power sharing of the microgrids. It is showed that the inverters can accomplish accurate reactive power sharing below the proposed regulator if the communication network of inverters is connected. Under the standard decoupling guess for bus angle differences, the reactive power flow of each inverter is reliant on the voltage amplitudes of its adjacent inverters connected by electrical power lines. Both the suggested controllers are legalized by simulations on a collection of inverters with time-varying loads. For inductive impedance loads and below the guess of small phase angle modifications between the output voltages of the inverters, we show that the choice of the control parameters exclusively determines the consistent equilibrium Point of the closed-loop voltage and reactive power dynamics. Simulations and investigational results show that the developed droop controller can share load active and reactive power, advance the power quality of the microgrids and also have a good dynamic act. Finally, the future research trends on islanded microgrids are also deliberated in this paper.*

Index Terms-Distributed control, power-sharing control in islanded microgrids with event-driven communication, reactive power sharing.

1. INTRODUCTION

Currently, the number of renewable energy sources connected to the communal grid is increasing significantly due to the deregulation of the electric power distribution industry and to environmental issues. Until now, renewable generators are always being grid-connected, injecting all the generated power to the grid. Essentially, it is scientifically possible to group some renewable generators, energy storage components and local loads, and work alone as microgrids. An MG is formed by altered energy generators connected to a point of common coupling (PCC) that feeds local loads and can work alone or connected to the mains. These small grids must be able to generate and store energy near to the intake points. This avoids large distribution lines coming from big power plants located far away from the consumption areas, thus reducing transmission losses and improving system reliability. The MG should be able to operate connected or disconnected from the grid. These operation procedures are called grid-connected and islanded modes respectively.

Important components in power systems are so-called grid generating units. In AC networks, these units have the charge to deliver a synchronous frequency and a definite voltage level at all buses in the network, i.e., to deliver a stable operating point. Studying under which conditions such an operating point can be delivered and conserved, naturally pointers to the problems of frequency and voltage stability. In conventional power systems, grid-forming units are DGs. further frequency and voltage stability, power sharing is an important act standard in the operation of microgrids. Here, power-sharing is agreed as the capability of the local controls of the separate generation sources to achieve a preferred steady-state distribution of the power outputs of all generation sources comparative to each other, while satisfying the load demand in the network.

The relevance of this control objective lies within the fact that it allows to pre-specify the utilization of the generation units in operation, e.g., to prevent over loading. The like to accentuate that reactive power sharing by the management of the voltage amplitudes is of specific practical interest in networks or clusters of networks, where the generation units are in close electrical proximity. This is often the case in microgrids and we only consider such networks in this paper. Then, the line impedances are relatively low, which from the standard power flow equations, implies that small variations in the voltage sufficient to achieve a desired reactive power-sharing. Also, close electrical propinquity usually implies close geographical usually implies a close geographical distance between the different units, which facilitates the practical implementation of a distributed communication network.In addition to the frequency/voltage balance and renewal problems, the power-sharing task is a mutual practice in microgrids as different types of generators may have different power generation capacities.

Then, appropriate power-sharing strategies should be developed to adjust the power injections of generators to satisfy the capacity constraint, building a desired distribution of the power outputs to meet the load demand in the microgrids. Effective sharing of active and reactive powers among generators is, thus, an important performance criterion. Since the generators are heterogeneous and may be placed at different locations, distributed control and management strategies are required to improve the stability, scalability, and security within the microgrids for the power-sharing problem, primary droop control is a widely used method and can be implemented in a decentralized manner with centralized information processing active and reactive powers are measured for each generator to perform feedback control. The errors between the power set points and the measured power flows are taken as feedback signals to set the frequency and voltage amplitude for the inverters. Although this method can achieve power-sharing with simple local controllers for inverters, the accuracy is low, especially when the loads change. In a new droop control method based on error decrease and voltage, recovery operations have been proposed to improve the accuracy of reactive power sharing.

First, we propose a Lyapunov-based design approach for reactive power-sharing control. Related to the consensus-based approach in and our approach is simpler in union analysis and the condition for doing power-sharing is clearer in expression and easier to verify.

Second, the proposed event-driven controller is droop-based without introducing an additional secondary control. Thus, it can achieve faster and more accurate reactive power sharing than the control line.

The recreation of this paper is planned as follows. Section 2 kindnesses the electrical and communication network simulations, inverter models of the microgrids, and the description of related power-sharing.

In Section 3, the proposed continuous and event-driven power-sharing regulators are provided with junction analysis.

In Section 4, the models for microgrids with six inverters are shown under the two proposed controls to show their efficiency in comparative power-sharing with varying loads. Finally, this paper is concluded in Section 5.

2. DESCRIPTION OF THE MG SYSTEM

2.1 Islanded Micro-Grid system

The MG deliberated in this paper is collected by variously distributed generators (DG) fed on changed renewable power sources that are coupled to a PCC and exact by a central USC, as illustrated in Figure 1_a. According to the topology reflected in this work, a group of local loads is coupled to the PCC, requiring the appropriate amount of active and reactive (P/Q) power for its proper operation. In order to assemble the power-sharing control approach, a smart sensor placed at each load is in charge of sensing the load consumption. In addition, a communiqué network relating all the inverters, the load sensor and the USC is measured. The USC will be responsible for the situation the power situations to each DG, allowing a correct power-sharing among them. Figure 1_b shows the diagram of each DG based on three phase three-wire inverters. Each inverter is connected to the PCC concluded an LCL filter. The control block exposed in the figure will drive the inverter switches in order to inject the required P/Q references. It is assumed that the LCL capacitor voltage, v_o, and the inverter current is I, are identified nearby by each inverter.

In this section, the power flow model is presented and then simplified. Let the angle difference between node *i* and node *l* be $\theta_{il}= \theta_i - \theta_l$. The active and reactive power flows from node *i* to node *l* are

$$P_{il} = G_{il}V_i^2 - \sum_{l \in N_i^l} V_i V_l (G_{il}\cos(\theta_{il}) + B_{il}\sin(\theta_{il})) \quad (1)$$

$$Q_{il} = -B_{il}V_i^2 - \sum_{l \in N_i^e} V_i V_l (G_{il}\sin(\theta_{il}) - B_{il}\cos(\theta_{il})) \quad (2)$$

Where V_i is the voltage amplitude of node *i*. The total active and reactive power flows at node i are,

$$P_i = G_{ii}V_i^2 - \sum_{l \in N_i^e} V_i V_l (G_{il}\cos(\theta_{il}) + B_{il}\sin(\theta_{il})) \quad (3)$$

$$Q_i = -B_{ii}V_i^2 - \sum_{l \in N_i^e} V_i V_l (G_{il}\sin(\theta_{il}) - B_{il}\cos(\theta_{il})) \quad (4)$$

$$S_i = P_i + jQ_i \quad (5)$$

$$G_{il} = \widehat{G_{ıı}} + \sum\nolimits_{l \in N_i^e} G_{il} \text{ and } B_{ii} = \widehat{B_{ıı}} + \sum\nolimits_{l \in N_i^e} B_{il} \quad (6)$$

The objective of this paper is to develop distributed controllers for accurate reactive power sharing. To simplify the electrical network model and facilitate both presentation and mathematical development, the standard decoupling approximation which adopts small bus angle differences is employed we assume that,

$$Q_i = |B_{ii}|V_i^2 - \sum_{l \in N_i^e} |B_{il}|V_i V_l \quad (7)$$

$$|B_{ii}| \geq \sum_{l \in N_i^e} |B_{il}| \quad (8)$$

Where $|B_{ii}| \geq \sum_{l \in N_i^e} |B_{il}|$ the reactive power flow can be controlled by the voltage amplitude of itself and its electrical neighbors.

2.2 Communication Network Model

The expected voltage control is distributed and involves communication among generation units in the network. To describe the high-level properties of the communication network, a graph-theoretic notation is used in the paper. We assume that the communication network is represented by an undirected and connected graph G = (V, E). Furthermore, we assume that the graph contains no self-loops, i.e., there is no edge e_l = {i,i}. A node presents an individual agent. In the present case, this is a power generation source.

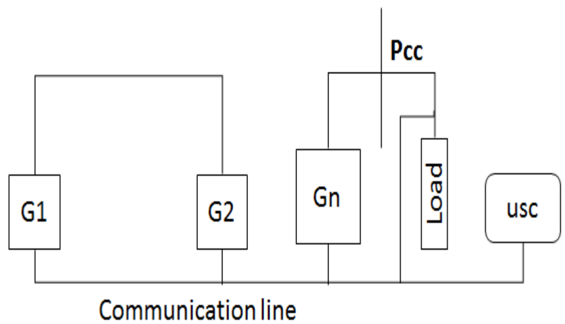


Fig (1): communication n/w model

If there is an edge between two nodes i and l; then i and l can exchange their local measurements with each other. The nodes in the communication and in the electrical network are identical, i.e., $N \equiv V$.Note that the communication topology may, but does not necessarily have to, coincide with the topology of the electrical network, i.e., we may allow $C_i \neq N_i$ V for any,

$$a_{il} = \begin{cases} 1, if\ l \in N_i^c \\ 0, oterwise. \end{cases} \quad (9)$$

2.3 Inverter Model

The model of inverters as AC voltage sources the amplitude and frequency of which can be defined by the designer. Then, an inverter at node $i \in N$ can be represented the inverter model of node I can be represented by the following equations,

$$\theta_i = u_i^\theta \quad (10)$$
$$\tau_i \dot{V}_i = -V_i + u_i^V \quad (11)$$

Where θ_i and V_i are the output angle and the voltage amplitude of inverter i, respectively. U_i^θ And U_i^v are the control inputs to be determined. τ_i represents the input delay constant of the voltage. This model implies that the inverter is considered as a controllable ac voltage sources and its amplitude and frequency can be controlled by the inputs U_i^θ *and*.U_i^v Since we only consider the reactive power flows, the dynamics of θ_i are neglected in the sequel of this paper. Moreover, we assume that the voltage of the inverter has a very fast adjusting rate and thus $\tau_i \approx 0$. Then, the inverter voltage and the reactive power node i have the following model.

$$V_i = u_i^v \quad (12)$$

$$Q_i = |B_{ii}|V_i^2 - \sum_{l \in N_i^e} |B_{il}|\, V_i V_l \quad (13)$$

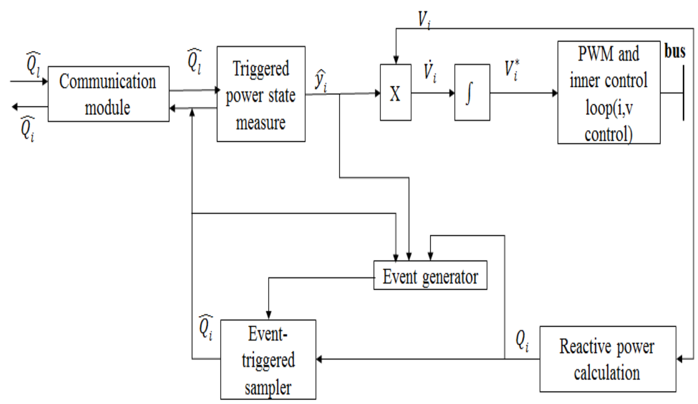


Fig (2): PWM inner control loop and communication module

Where Q_i is the reactive power of inverter i, B_{ii} is the susceptance inverter i, B_{il} is the susceptance between inverter i and j, and N_i^erepresent the electrical neighbor set of inverter i.

3. DISTRIBUTED REACTIVE POWER SHARING

3.1 Distributed Voltage control

Altered from the conservative droop control, we will propose a distributed voltage controller with inverters' state communication for reactive power sharing. Since the voltage control model is basic in $u_i^v(t)$becomes the voltage reference for inverter i. We design the following reference for inverter i,

$$u_i^V(t) = V_i^d - \int_0^t u_i(\tau)d\tau \quad (14)$$

Where $V_i^d$the desired voltage magnitude and u_i *(t)* is the voltage control input for inverter i and will be determined by feedback signals. Such design implies that for reactive power-sharing, the conventional Q_V droop control has been replaced by $\dot{Q}_v$droop control, which can improve the accuracy in power-sharing. By differentiating V_i with respect to t, the dynamics for node i.

3.2 Direct Control Methods for the Reactive Power Sharing

The highest assignment of through control methods for the reactive power sharing is to get the necessary value in each DG, do the sum of these values, and then assign these agreed powers to each DG on average. In each converter is responsible for providing the information of the required reactive power to the MG via low bandwidth communications links. In addition, the MGCC determines the way that how the reactive power supplies for each converter. Fig shows a distributed control scheme for eliminating reactive power mismatched in an islanded MG, where the reactive power Qi obtained from the droop control is sent to the secondary control to make a sum, and the Qi * obtained from the secondary control is sent to the primary control through PI controller. Moreover, the return of the droop control E^* is adjusted by Δ_{E1}. The reactive power demand Qi^* for each converter can be calculated by,

$$Q_i^* = \frac{\sum Q_i}{n_i\left(\sum_{i-1}^{k}\frac{1}{n_i}\right)} \quad (15)$$

Where ΣQ_i is the total reactive power provided by all the converters. Q_i^* is the reactive power request supplied to the i^{th} converter and n_i is the sag improvement of the i^{th} converter. The MG_{CC} is liable for regulating the reactive powers allowing to the reactive power situation of each converter, and the communication delay $G_d(s)$ is defined as:

$$G_d(s) = \frac{1}{T_d s + 1} \quad (16)$$

The control method shown in Fig can solve the problems of the corresponding or relative reactive power sharing with a sure communication delay. The values of the reactive power are removed directly and not affected by load impedance, thereby this control method is suitable for both the linear and nonlinear load situations. However, the communication delay is always uncertain and it may result in a poor reactive power sharing.

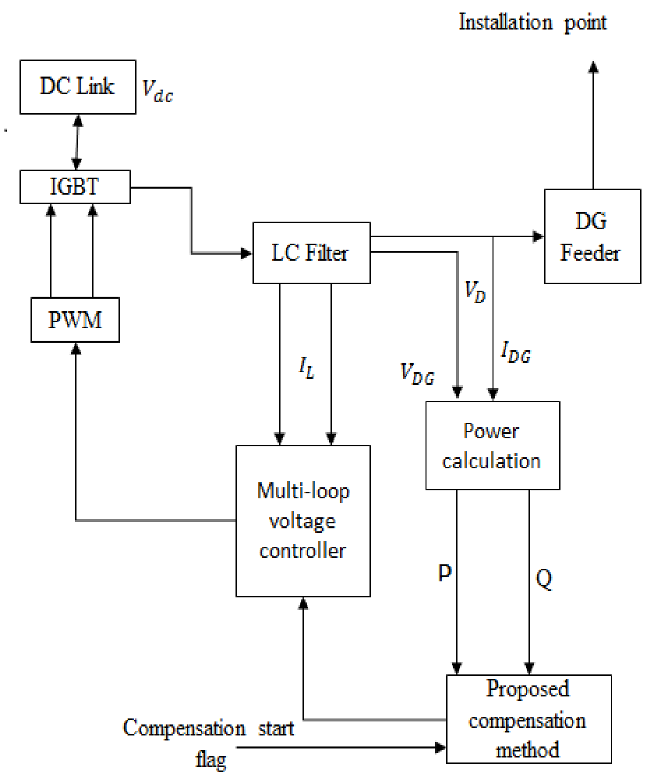
4. CASE STUDIES

The effectiveness of the proposed distributed controllers is validated by the simulations based on an islanded microgrids. The networked system consists of six inverters operating in parallel and supplying a variable load, as shown in Fig. Assume that the frequency of each inverter is dominated by a conventional droop controller described in the inverter only requires P_i, i.e., the active power measurement of itself, to conduct conventional frequency droop control, there is no need to transmit the active power states by the communication channels. Thus, the frequency droop control is actually distributed. For the suggested voltage controllers, reactive power states must be sent to adjacent inverters through the communication network. In this section, for case studies, the communication network of the inverter group is shown in Fig. There is no central node/inverter to perform as a position in this network, and thus, the entire control structure of the microgrids is distributed.

In this microgrid, the nominal voltage amplitude and frequency of the microgrids are 400 V and 50 Hz, respectively. Each inverter is associated with a reactive power rating S_N= (0.54, 0.72, 0.34, 0.66, 0.45, 0.26)pu and the base reactive power is assumed to be S_{base} =3k_{VAR}. The weight coefficients for the reactive power sharing are selected as the multiples of the nominal power rating $X_i = 3S_i^N$ for i = 1, 2, 3, 4, 5, 6. The feedback gains of the controllers are chosen as κ = 2 × 10−5 var−1. For each inverter, we set the desired voltage amplitude as$V_i^d = 1pu$ not affected by load impedance, thereby this control method is suitable for both the linear and nonlinear load situations. Though the communication delay is continuously indeterminate and it may result in a poor reactive power-sharing.

4.1 Load-Change Operation

The USC will be aware of a load change since the smart sensor is updating this information according to its specifics. Though it is significant to note that not all variations in the load depletion may need a change in the inverters settings. So, a new design stricture comes into play, which refers to choose when it is worth to update the inverter settings for a capable power-sharing control operation following the same approach used in the smart sensor communication, the message from the USC to the inverters will also follow a send-on-delta policy.



Fig(3): Illustration of microgrids configuration

Therefore, another design parameter is the threshold Δ_{USC} that determines the allowable error between the last sent P^{usc}_{sent} sent or Q^{usc}_{sent} sent from USC to inverters, and the latest sent P_{load} or Q_{load} from the smart sensor to USC. Therefore, two new beginningsΔ^{P}_{usc} and$\Delta^{Q}_{usc}$are required for the send-on-delta operation.

The data exchange is illustrated in the bottom part of Figure. Also, Figure shows the pseudocode that enables this communication. Although the pseudocode is executed due to the reception of the incoming message, it could be executed according to other events if required. In any case, the generated data exchange from USC to the inverters will be event-triggered, and the amount of generated network traffic will depend on the design.

4.2 Fault operation

In faulty operation, the MG nominal power will radically change. Therefore, this situation should be properly managed by the USC to keep the power-sharing control, that is, new PMG should be computed and sent to the still alive inverters.one approach for detecting a faulty inverter could be to have each inverter sending a keep-alive message periodically to the USC. When one of these messages is not received, the USC could infer that a particular inverter is not working anymore. A major problem with this approach may be an excessive bandwidth consumption for the communication infrastructure the approach presented here is radically different. The idea is to detect the faulty inverter using data available from the MG and issue the corresponding event. To prepare so, the VSI inverter approaches into play and associates the active and reactive power orientations P and Q with the inserted measures P_{inj} and Q_{inj}. Thus, it can identify if it is injecting more power than it would be, that is, it detects an overpower feeding in the VSI. The VSI computes the POC as

$$P_{OC} = \left(\frac{P_{inj}}{P_{load}} - CF_{inv}\right) P_{MG} \qquad (17)$$

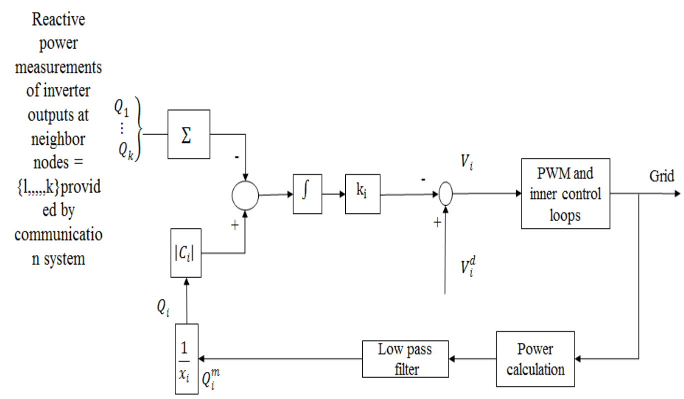


Fig (4): Fault operation measurement of reactive power

The POC denotes the nominal power of the faulty inverter. Though, the extra power addition of the VSI can be due to a conversion of load or a faulty inverter. In either case, an event is created at VSI, which means that a specific message having POC is sent to USC. In case of a load change, the USC previously knows this change and forgets the message coming from the VSI. Otherwise, an "alarm" situation is known. In the latter case, the USC must calculate the new PMG and re-send it to all inverters in a message having the new PMG, and the known P_{load} and Q_{load}. The calculation of the new PMG at USC is as follows,

$$P_{MG} = P_{SV} - P_{OC} \qquad (18)$$

Where PSV is the previously shown rate for PMG. The figure shows the statement between USC and the VSI when an inverter of the MG is the blackout.

5 SIMULATION

The simulated islanded MG has six inverters with the same small power PINV = 3kV A, whose bounds are given in Table I. For simulation purposes, each inverter has a tolerance of 20% on these factors. However, all of them have the same convert factor value, CFINV = 1/3. These six inverters can work as VSI and CSI. The only one of them acts as VSI and the other two as CSI. The MG loads are composed of RL loads connected in parallel with nonlinear loads considered by rectifiers and RLC elements. The following sections show selected simulations for the start-up operation, the load-change operation, and the faulty operation.

5.1 Simulation for system start-up

The first simulation illustrated in Figure shows the power-sharing control strategy between the three inverters. To ensure a soft start-up process, E_0^* is ramped up from 0 to V_{PCC} in one grid cycle. This can be observed in the top sub-figure, where the load voltages take 20ms to achieve the steady-state value.

In addition, since the conversion factor of all inverters is the same, at the steady-state operation, all of them deliver the same power, as observed in the bottom subfigure. The transient behavior is explained as follows. In order to cope with the non-linear loads, a filter with a crossover frequency of 25Hz is applied in the smart sensor. The effect of this filter is a delay in the measurement of the power load. And this ends up in achieving the steady state slowly.

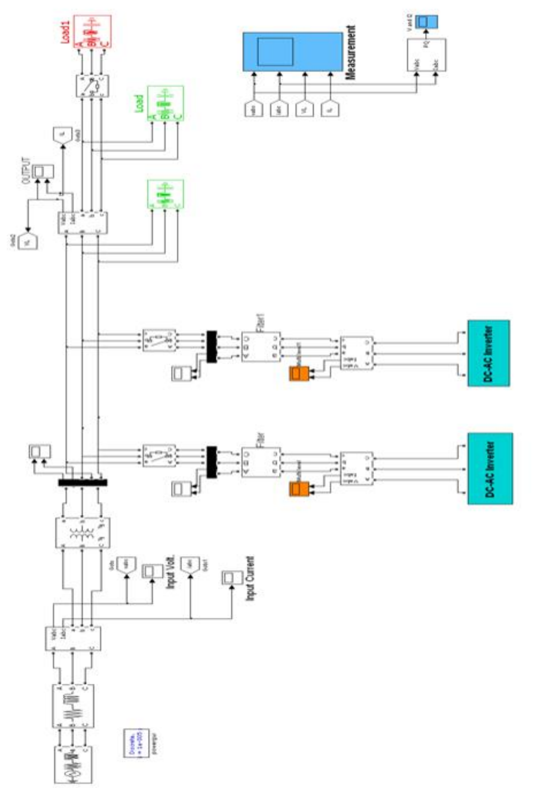


Fig (5): Electrical microgrids simulation diagram

Table [1]: system parameter

parameters	value
V_{pcc}	$220\sqrt{2}[V]$
ω	$2\pi 50[rad/s]$
L_i	$5.5[mH]$
c_o	$0.5[\mu F]$
L_o	$1.4[mH]$
R_{lode}	$33.3[\Omega]$
L_{lode}	$100[mH]$
P_{INV}	$3KVA$

The difference between the power delivered by the VSI and the two CSI is due to the fact that the power demanded by the load is firstly served by the VSI.

5.2 Simulation for load change

The figure shows the behavior of the power-sharing control strategy when a load change occurs. In particular, the figure shows in the top subfigure the load voltage and in the bottom subfigure the measured power at the load. Looking at the bottom subfigure, it can be observed that the load changes to a double consumption, from 3kW to 6Kw at time 0.2s. And despite this change, the load voltages have only a small transient dynamics that does not affect the overall operation.

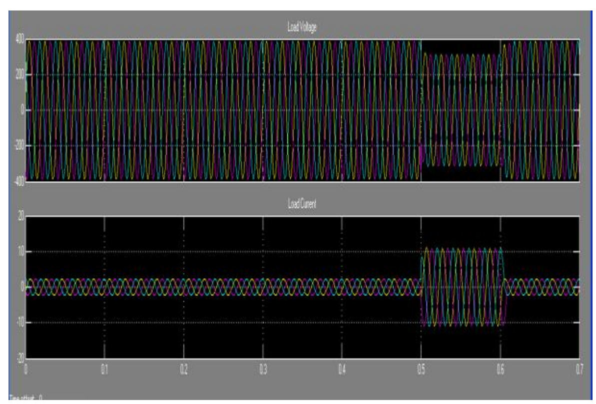


Fig (6): Load voltage & Load current change

Hence, this corroborates the goodness of the VSI controller. In the following, simulation results will illustrate the behavior of the communication strategy. To simplify, only changes in P are reported. To this extent, the threshold in the smart sensor and the USC are both configured to send changes bigger than 5% with respect to the last sent measurement. That

$$\Delta_{ss}^{P} = 5\% P_{sent}^{P^{ss}} \; and \; \Delta_{usc}^{p} = 5\% P_{sent}^{usc} \tag{19}$$

Therefore, the load change is supported by the three inverters.

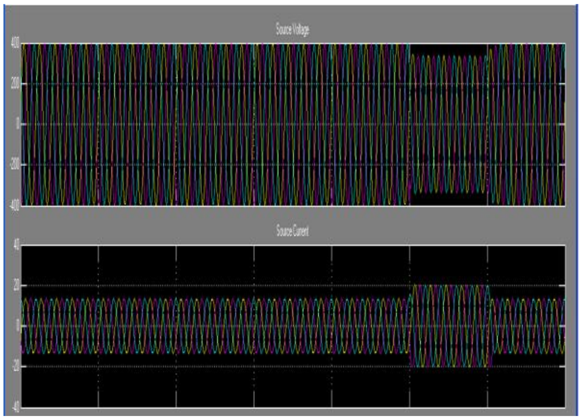


Fig (7): Source voltage & Source current demand duration

First of all, load changes bigger than 5% are considered. The figure shows in the top subfigure the power measured in the smart sensor. And the bottom subfigure shows the power references $P^*$and Q^* in one of the CSI inverters. As it can be seen, when the measured load changes, the power references change thanks to the communication strategy. However, Figure shows the same information than the previous figure when changes are smaller than 5%. In can be observed that in front of small changes in the measurements, the power references are not changed. This method avoids unnecessary communication between the smart sensor and the USC, and between USC and inverters. In this case, the load change is only assumed by the VSI.

5.3 Simulation for Faulty Operation

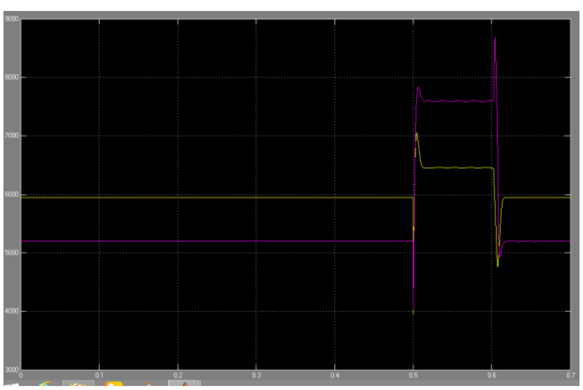


Fig (8): Active & Reactive power demand duration

By the different data, the remaining CSI inverter changes its power location by applying. That way, all inverters in the microgrids pullout the same percentage of their self-nominal power. The figure expressions the manner of the system in the presence of an inverter failure.

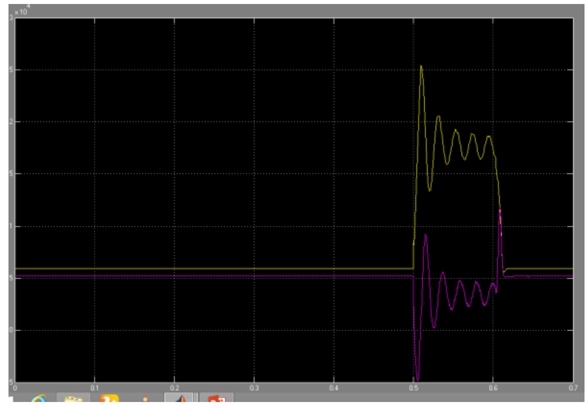


Fig (9): Improve the active & Reactive power

Note that in this case, a radical change of the MG nominal power occurs. In particular, the top subfigure shows the power inserted by each inverter and the bottom subfigure shows the P_{MG}. As it can be seen in the top subfigure, at time 0.3s, a CSI inverter disappointment occurs. After the VSI discovers this situation, it sends a P_{OC} message to the USC. Then the USC re-calculates the new P_{MG} as showen in, and at time 0.308s sends this new factor collected with the existing P_{load} and $Q_{load.}$

6 CONCLUSION

In this work, a compacted controller for islanded microgrids was existing. An incident based communication link was used to develop a compacted controller that allows local load power-sharing control. Different distributed renewable power sources are connected to a point of a common combination through three-phase three-wire six inverters. All the inverters feed Co-operatively linear and non-linear local loads. One of the inverters of the MG works as a voltage source and sets the correct PCC voltage and frequency to feed locals loads in islanded mode. The other distributed sources that form the MG act as current sources, being simply voltage follower s that follow the active and reactive power orientations set by a compacted controller. The desired features of the proposed power-sharing strategy have been agreed by means of selected simulation results. The simulations results have shown good dynamic performance during load changes and faulty operation. Also, the tests show that several inverters can be plugged-in or out while protection overall system reliability. Some issues have been left for future work, among them, the faulty operation of the VSI needs a special attention.

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