Load Sharing by Decentralized Control in an Islanded Voltage Source Converter-based Microgrid Considering Fixed Frequency

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Abstract

Background/Objectives: In this paper by utilizing frequency tracking electrical loads are shared on voltage source converters and then by applying a proposed-supplementary control system, frequency changes during changing electrical loads inside network is omitted. Methods/Statistical Analysis: Using decentralized control in Microgrids and sharing loads on power generation units respect to their nominal capacity are unavoidable approaches to have stable and operational network. Droop control in load sharing is known as practical and significant solution. In droop control, units output frequency, changes proportional to output active power that is not preferable. Simulation results in PSCAD are performance confirmation of proposed control system. Findings: In proposed-supplementary control system, in spite of applying droop control to share loads, nominal frequency of all power generation units are fixed in a floating way while changing output active power. Applications/Improvements: Applying proposed-supplementary control system on droop control makes microgrids appropriate for electric loads which are sensitive to frequency changes.

Keywords: Decentralized Control, Frequency Stability, Load Sharing, Microgrid, Voltage Source Converter

1. Introduction

Utilizing Distributed Generations (DG) in today’s power systems causes change to electrical energy generation and supplying electric loads inside grid. Indeed, an increase in electric energy consumption and economic, technical and environmental constraints, make DG utilization in power systems inevitable. In addition, by utilizing DGs the reliability of the power system will rise and there is no need for expansion in large scale generation units. Improvements in power quality indexes, better voltage regulation and power factor correction are other advantages of DG utilization that in central generation systems are dramatically less feasible. By reducing distance between generation units and electrical loads, power loss in transmission and distribution system would be decreased and ancillary services such as reserve systems and reactive power compensation are provided by DGs.

Microgrids are taken into consideration in a way that they are a place for gathering DGs. In other words, a Microgrid is defined as a small power system that composes of DGs, Energy Storage Systems (ESS) and various thermal and electrical loads. In addition, a small islanded-power system is known as a typical issue in various applications such as naval electric ships. By raising new concerns about availability of fossil fuel resources and cost of energy generation, renewable energies as DGs play major role in Microgrids.

Power Electronic Interfaces (PEI) in microgrids have been always studied due to existence of energy resources with small capacities that are not capable of connecting to network directly. This matter has brought up Voltage Source Converter-based
Microgrids\textsuperscript{5}. Therefore, in these microgrid types, energy resources, either DGs or ESSs, should be capable of plugging and playing to network without any significant impact on stabilizing Microgrid\textsuperscript{9}. One of the most used PEIs applied in microgrids are Voltage Source Converters (VSC). Control terms of VSC that guaranty right performance of a microgrid have been addressed in\textsuperscript{10} and\textsuperscript{11} that investigated on output voltage phase and amplitude in VSCs.

For microgrids two operation modes have been defined; Grid-Connected and Islanded mode\textsuperscript{12}. In Grid-Connected mode, DGs inside Microgrid follow bulk power system parameters (voltage and frequency) and inject their available power to network. In this mode, PEIs are configured under current control strategy\textsuperscript{13}. Some approaches have been introduced to share power in grid-connected microgrids\textsuperscript{14}. Also microgrids have been taken into consideration in autonomous operation. In autonomous operation of microgrids stabilizing frequency and voltage inside network is on VSCs' shoulder. Various centralized and decentralized methods have been defined to control islanded microgrid\textsuperscript{15,16}.

Parallel operation of PEIs in a microgrid has numerous advantages than central supply systems such as better reliability, improved dynamic response and easy equipment maintenance\textsuperscript{17}. One of the important issues in stabilizing a Microgrid including PEIs is load sharing among power generation units that will be covered in ongoing parts of this paper. Droop control is applied in an islanded microgrid in order to share electric loads and have decentralized control. In droop control by changing VSCs' frequency, the output active power is controlled and loads are shared on them. Therefore, frequency alternation always exists. Maintaining frequency constant is a new issue that attracts attention to develop new methods such as robust PI controller\textsuperscript{18}. In this paper by utilizing a Proposed-Supplementary Control System (PSCS) in droop control structure, in addition to retain advantages of this method in load sharing and stabilizing, frequency alternation would be omitted in all operation set points. As a result the frequency of network would be kept unchanged.

In following parts, load sharing and droop control is introduced in the second part. Then in next section, PSCS is defined and afterward in fourth section by implementation this control system on two different networks, its performance is investigated. The last section is released as conclusion.

2. Load Sharing and Droop Control

As mentioned in previous part, in order to have stable network all electric loads should be shared on power generation units. In centralized control it is necessary to have communication lines between VSCs and a central control unit to process received data from network and send required signals to VSCs\textsuperscript{15,16}. Therefore, this matter make microgrids structure more complicated and in case of far distances between VSCs, sharing dynamic signals would be costly and unpractical\textsuperscript{19}. Accordingly, decentralized control has been introduced as an effective method to overcome disadvantages of centralized control\textsuperscript{19}. An inverter-based microgrid supplies electric loads through PEIs from distributed energy resources. Lack of inertia in PEIs matters when it is desired to have stable network with two or more generation units. As a result, for these types of networks, acting like conventional power system is unreachable. In addition, DGs generally are considered as low capacity units and they are in charge of keeping balance between supply and demand. To direct this issue many articles have been conducted and it has attracted many studies and investigations\textsuperscript{20,21}.

Active power/frequency (P/f) characteristic in droop control has a similar structure in reaction of conventional power systems to demand change\textsuperscript{22}. On the other hand, to control and stabilize voltage within the network, reactive power is shared on units after implementation of reactive Power/Voltage (Q/V) characteristic in droop control\textsuperscript{23}. In some references it is claimed that droop control according to P/f and Q/V is applicable in networks with dominantly inductive communication lines and because of resistive structure of microgrids, P/V characteristic should be applied\textsuperscript{23}. Figure 1 illustrates P/f characteristic of three VSCs in a Microgrid. Reference\textsuperscript{23} has presented comprehensive terms of droop control in load sharing on VSCs.

To better understanding droop control performance and getting familiar with variables in Figure 1, parallel operation of VSCs has been studied.

First of all, a simple network with two VSCs and a common load is presented. Figure 2 shows a schematic structure of the mentioned network.

In Figure 2 each VSC unit supplies loads respect to its nominal capacity. To apply droop control on VSCs, Equation (1) is introduced as the main term in this field:

\[ f_1^* = f_n + K_{fP}(P_n - P_{n0}) \quad (1) \]
non-linear loads and harmonics, static droop control and etc. have been introduced and represented. Beside mentioned advantages, some disadvantages can be named as main cons of utilizing this kind of control system:

- Droop control method is sensitive to output impedances of VSCs and communication lines inside Microgrid.
- Droop control has weak voltage and frequency regulation.
- Droop control is extremely dependent on droop coefficients and in some cases unsuitable coefficient values cause instability in network. If highly accurate load sharing is preferable, microgrid parameters will exceed predefined limits and if low frequency drop is considered, load sharing and network dynamics will not be acceptable.

In this paper by applying Frequency Tracking (FT), droop control in a microgrid has been implemented. This method has reduced the dependency between communication lines and droop control. Then by applying PSCS on FT, the frequency of network in sharing active power by droop control has been remained unchanged and set to nominal predefined value. As a result the weak point of droop control in frequency regulation inside network has been addressed.

3. Proposed-Supplementary Control System (PSCS):

At the beginning implementation of FT is explained. Then PSCS is applied on it. The principle of droop control has been based on small signal analysis that includes some assumptions such as synchronous dq axis for all VSCs. In addition, conventional droop control in small changes inside network responds properly. Nevertheless, big changes like heavy loads or main generation units outage are probable within a microgrid. FT control system is useful method in implementation of droop control according to discussed subjects.

Before conducting mathematical equations of FT, it is recommended to refer Figure 2. By assuming that two VSC units have different nominal capacity and naming Unit 1 and 2 as master and slave respectively, the conventional droop control system has been applied to mentioned-microgrid.
In other words, VSC no 1 generates its nominal active power with the nominal frequency (50HZ). In FT other units are forced to track the frequency of master unit. Therefore, control system structure should prepare this issue. In order to achieve mentioned goal, by utilizing a PI controller in control system of the VSC no 2 frequency error between two VSC units is eliminated. Figure 3 illustrates applied PI controller in control system generally. In Figure 3 variables are defined as below:

- $f_1$: Generated frequency of master unit after applying droop control.
- $f_b$: Defined frequency for slave unit after applying droop control.
- $f_2$: Directed output frequency to slave unit.

In microgrids including VSCs, owing to have decentralized control, frequency and generated power of each unit cannot be set by signal commands. Therefore, a control method should be presented that in addition to stabilize frequency, controls microgrid in a decentralize way and during stable operation, loads inside network should be shared accurately. Figure 4 shows the FT performance for the Unit no 2.

In FT, in order to have fixed frequency in network, output frequency of each unit tracks master unit’s frequency. It is done by adding a PI controller to droop control structure. Indeed, PI controller changes instantaneous frequency of each unit to make frequency disparity zero in stable operation.

According to Equation 1 and control structure of FT, Equation (3) can be determined as the output frequency of the Unit no 2 that is measured on the terminal as defined below:

$$f_b = f_n + K_{fp2}(P_{n2} - P_{o2})$$

(3)

In ongoing parts of this section, the transfer function of control system is extracted to generate frequency signal of the Unit no 2. Equation (4) shows terms of output frequency for the Unit no 2 respect to frequency change in Unit no 1 (master) and droop characteristic of VSC no 2:

$$f_2(s) = \frac{k_p + k_i}{s} \times f_1(s) + \frac{1}{1 + k_p + \frac{k_i}{s}} \times f_b(s)$$

(4)

In Equation (4), the values of $k_p$ and $k_i$ are proportional and integrator coefficients of PI controller respectively.

$$\lambda = -\frac{k_i}{1 + k_p}$$

(5)

Therefore, Integrator in control system for stabilizing microgrid is necessary when changes occur.

To better introduce the transfer function, we rewrite Equation (4) as Equation (6).

$$f_2(s) = \frac{k_p + k_i}{s} \times (f_n + k_{fp1}P_{n1})$$

$$- \frac{k_p + k_i}{s} \times (k_{fp1}P_{o1}(s))$$

$$+ \frac{1}{1 + k_p + \frac{k_i}{s}} \times (f_n + k_{fp2}P_{n2})$$

$$- \frac{1}{1 + k_p + \frac{k_i}{s}} \times (k_{fp2}(P_2(s) - P_{o1}(s)))$$

(6)

In Equation (6), generated frequency signal has been shown by Unit no 2 respect to $P_{n1}$ and $P_{o2}$ as input signals for control system.
In the system that consists of two generation units, total requested active power in network is sum of each unit’s active power, as a result:

\[ P_l = P_{o1} + P_{o2} \]  \hspace{1cm} (7)

Therefore, by placing Equation (7) in Equation (6), the frequency change in Unit no 2 for load changes in the network and Unit no 1, can be calculated as Equation (8).

\[
\begin{align*}
\Delta f_2(s) &= \frac{k_p + \frac{k_i}{s}}{1 + \frac{k_p}{s}} \times (f_n + k_{fp2} P_{o1}(s)) \\
&- \frac{k_p + \frac{k_i}{s}}{1 + \frac{k_p}{s}} \times (f_n + k_{fp1} P_{o2}(s)) \\
&+ \frac{1}{1 + \frac{k_p}{s}} \times (f_n + k_{fp2} P_{o1}(s)) \\
&- \frac{1}{1 + \frac{k_p}{s}} \times (k_{fp2} (P_l(s) - P_{o1}(s)))
\end{align*}
\] \hspace{1cm} (8)

For better illustration of power changes in network, step function has been used. As a result, the load of entire network suddenly alters from \( P_{l1} \) to \( P_{l2} \). Generated power by Unit no 1 according to the droop characteristic will change as step. Step change in active power demanded by the grid and generated power of the Unit no 1 in (s) space have been shown in Equations (9) and (10):

\[
P_l(s) = \frac{\Delta P_l}{s}
\]  \hspace{1cm} (9)

\[
P_{o1}(s) = \frac{\Delta P_{o1}}{s}
\]  \hspace{1cm} (10)

Changes in steady-state output frequency of the Unit no 2 are calculated according to Equation (11):

\[
\Delta f_2(t) = -(k_{fp2} \times \Delta P_{o2})
\]  \hspace{1cm} (12)

If we consider Equations (11) and (12) it is proved that:

\[
(k_{fp2} \times \Delta P_{o2}) = (k_{fp1} \times \Delta P_{o1})
\]  \hspace{1cm} (13)

Thus:

\[
\frac{k_{fp1}}{k_{fp2}} = \frac{\Delta P_{o2}}{\Delta P_{o1}}
\]  \hspace{1cm} (14)

Equation (14) is the provision of load sharing on units using droop control which has been addressed in many references similarly\(^{26,30}\).

As mentioned in previous parts, the value of droop coefficient is significantly important in load sharing and dynamic performance of the network. The higher droop coefficient (in predefined limits), the better dynamic performance and load sharing would be implemented more accurate than small droop coefficients. Although frequency disparity would be high and in some cases by applying high droop coefficient, frequency magnitude crosses rated range. On the other hand, small droop coefficient has advantage of less frequency disparity from nominal value but load sharing and dynamic performance would be inaccurate and poor. Therefore, choosing droop coefficient is an important step in load sharing and decentralized control of VSCs. In this paper, with respect to advantages of high droop coefficient values, by applying PSCS the problem of frequency disparity is tackled and active power loads are shared on generation units respect to their nominal capacity in addition to have acceptable dynamics.

Now in order to fix frequency in predefined nominal value in a range of output power, it is possible to make rated frequency of each unit float. In this control system rated signal as an input is applied to each VSC as nominal frequency after passing below steps:

- Firstly, output frequency of a VSC is chosen as feedback signal.
- Then this signal is compared to predefined nominal frequency of the network.
- Afterward by applying a PI controller, error signal directed as an input.
- And the last step, output of this control system is directed to VSC as nominal frequency.

To better explanation, in order to analyze performance of PSCS, Equation (15) expresses Figure 5 in mathematical form:

\[
\Delta f_2(t) = -(k_{fp2} \times \Delta P_{o2})
\]  \hspace{1cm} (12)
According to the Equation (15) $f_i$ is the output frequency of the $i^{th}$ unit after applying droop control and FT. In addition, $f_{rated}$ is predefined frequency for network in order to be fixed. $K_p$ and $K_i$ are coefficients of proportional and integrator in PI controller respectively. Output signal of this control system ($f_n$) is considered as reference signal shown in Figure 3 and Equation (1). It should be noted that in conventional control systems and without applying PSCS, $f_n$ is set to 50 Hz and it is constant.

According to Figure 5 output frequency signal of a VSC is compared to 50 Hz and after passing through a PI controller it is applied to $f_n$ as an input. By this method the output frequency of each VSC is always set to predefined value and there is no discrepancy between them.

Figure 6 illustrates performance of PSCS during frequency drop respect to increase in the output active power on a VSC.

According to Figure 6, output active power of a VSC has changed from $P_{rated}$ to $P_{out}$. Therefore, according to FT and droop control the output frequency of this converter would change from $f_{rated}$ to $f_{out}$. In PSCS, operating point of this VSC, without any change in output active power, is directed to raise output frequency linearly. It should be noted that there is no change in droop coefficient in converters.

4. Simulation Results

To apply PSCS and FT on a microgrid control system and analyze simulation results, two networks with different structure have been studied. The first network is introduced as standard network and it has similar structure to Figure 2.

After derivation results from simulation, control system will be applied on a network with expanded structure including five VSCs and communication lines which are dominantly resistive and asymmetrical.

4.1 Network under Study No 1

To show performance of applied control system, a microgrid including two VSCs and dominantly resistive communication lines and centralized loads has been illustrated in Figure 7.

Table 1 in appendix 1 has presented values of parameters and variables associated with the network in Figure 7.

As it has been shown in Figure 7, each VSC has been connected to the network via an inductor ($L_1$ and $L_2$). In order to create asymmetric configuration in the
network, Inductors are considered non-equal. Nominal power of the Unit no 2 (Slave) is half of the nominal power of the Unit no 1 (Master). Therefore, we expect one third of the total power to be provided by the Unit no 2 in load sharing. Also the set droop coefficient of the Unit no 1 is 0.12. According to Equation (15), to have acceptable load sharing among units, the Unit no 2 droop coefficient of the Unit no 2 must be determined 0.24. Fixed and variable load values in 1 MVA base have been shown in Table 1 that on this operating point they designated for operation close to their nominal values and, at the end, network rated voltage and frequency, have been selected, 20KV and 50HZ, respectively. It is assumed that the permanent load is always connected to network, but variable load once is connected to network for five seconds and then removed. In fact, we tried to impose changes to the network to discuss the dynamic of changing power and accuracy of load sharing in the asymmetrical conditions.

Figure 8 shows simulation result of applying FT without PSCS.

In Figure 8 generated power of each unit has been shown. By applying FT to VSCs, demanded power respect to the nominal capacity of each unit has been shared. In addition, output frequency of units have experienced a gradual drop due to the load increase (in 5th second) and using droop control in FT. After variable load outage in 10th second, network’s frequency has returned to its previous value. In mentioned network all electric load have been shared on generation units accurately but the frequency changes should be taken into consideration.

Now after certainty about FT performance in mentioned network, PSCS is applied to network and Figure 9 illustrates simulation results.

According to Figure 9 illustrations, by applying PSCS, load sharing on generation units is conducted respect to their nominal capacity and the output frequency of generation units has been set to predefined value (50HZ) accurately. This is confirmation of proper functioning of control system on standard microgrid shown in Figure 7.

### 4.2 Network under Study No 2

Figure 10 shows the expanded microgrid. This network includes local and centralized loads and also communication lines are dominantly resistive. Indeed, the aim of utilizing this network is achieving the most asymmetry in structure and having more closed parameters to practical networks. The values of elements and parameters in network Figure 10 have been given in Table 2 (appendix 2).

The under-study microgrid composes of six communication lines that connect loads and generation units together. In addition, local loads have been installed in the network to have a practical microgrid. As illustrated in Figure 7, in addition to local loads, there are two main loads as variable and permanent centralized loads. As it is mentioned in Table 2 total capacity of network has been set to 2.3 MW. It should be noted that, it is assumed mentioned microgrid is capable of supplying loads more than its nominal capacity for a short period.

By applying PSCS beside FT to the network, simulation results are released as Figure 11.

According to Figure 11, by applying PSCS, no changes have been occurred in load sharing accuracy but the
output frequency of generation units have been set to predefined value (nominal value) accurately and there is no any overshoot or undershoot and even fluctuations in stabilizing frequency.

5. Conclusion

In this paper droop control by using FT is applied to the network. In order to stabilize frequency in load sharing on VSCs to a predefined value, a supplementary control system has been proposed. According to droop control performance in load sharing, active power changes inside network, cause frequency change in an islanded microgrid. By applying PSCS on reference frequency of VSCs, having a stable network without frequency change is achievable. Advantages of using PSCS beside FT are: Network frequency stabilizing, load sharing respect to nominal capacity of units, high speed dynamic response in load sharing, no sensitivity to network structure or communication lines and ability to add or remove more generation units without changing control system structure.

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