

STABILIZATION OF DC MICROGRID BY ACTIVE DAMPING METHOD

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Abstract—The paper proposes a method to damp the low-frequency oscillations produced in a hybrid source dc microgrid. A parallel combination of a photovoltaic (PV) system, a rectifier and a battery are used as a hybrid power conversion system (HPCS). The battery improves the slow transient response of the rectifier bridge. The HPCS controller consists of a multi-loop voltage controller and a virtual impedance loop for power management. The Mesh analysis is employed to further study the stability of low-frequency modes of the overall dc microgrid. The main highlight of the proposed method is its robustness. The project provides continuous supply of current to the load instead if one of the supply is being disconnected from the source side region. The proposed model can either be connected in islanded mode or grid-connected mode fashion. This feature provides DG units with plug-and-play capability without needing the exact values of microgrid parameters. The proposed model is very much useful in improving the power quality provided at the same time it also helps in improving the durability of the equipment connected to the load. The loading effect produced is greatly minimized to the maximum level.

Index Terms—Distribution generation, DC microgrid, maximum power point tracking, multiloop gain, hybrid powered source, robustness, uninterrupted supply.

1. INTRODUCTION

The system which is being used nowadays for damping the low frequency oscillations and improving the power quality are not much reliable and uses complex computations. The bidirectional power transfer utility takes place in a complex manner and this transition has been basically initiated by the employment of small scale distribution generation units and is being further facilitated by the advent of microgrids. Microgrids are the entities involving a number of DGs, energy storage systems and loads that are electrically interconnected. This architecture has the capability to operate either as a grid-connected or as an islanded system, and offers a promising solution for coordinated control of an aggregation of DG units. Generally, microgrids are categorized as ac, dc and hybrid ac-dc microgrids each providing particular benefits to the loads and the electrical network. AC microgrids have drawn an extensive attention on various aspects including interfacing converters, power sharing among parallel sources and power quality issues. The measurable value of dc power generated by renewable energy

sources, e.g., rectifiers, batteries, photovoltaic systems, and wind turbine systems, along with the rapid growth of loads are among the main driving factors for the development of dc microgrids.

Moreover, dc microgrids require structurally simple power electronic interfaces and provide more efficient energy conversion systems as compared to the ac microgrids. The dc microgrids are also easier to control as they do not need any frequency and reactive power regulations. The dc converters can efficiently operate in parallel connection mode. Thus, the dc microgrids offer more modular and scalable system. Robust stability and dynamic performance of microgrid systems in both grid-connected and islanded mode of operation are among main technical challenges. In the islanded mode, the control strategy has a more complicated structure as it must cope with voltage stability and power management among the DGs.

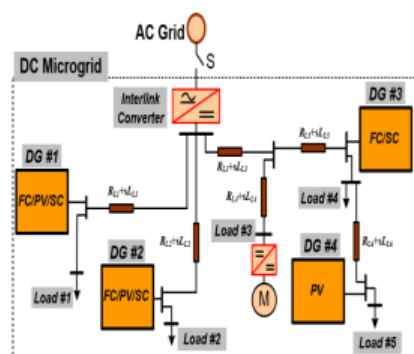
The stability margin and the dynamic behavior of converter-based DG units in a dc system basically differ from those of conventional ac systems. Thus, further researches are required to overcome the challenges of dc microgrids. It should be noted that an appropriate coordinated power management among the hybrid energy resources in dc microgrids will maximize the microgrid robust stability margin. The instability issues caused by constant-power loads in dc distribution systems, various techniques have been proposed in the literature. The load shedding, filtering, direct connection of energy storage to the main bus, and control approaches are among the well-known methods. The existing methods, however, do not investigate low-frequency instabilities in dc microgrids, imposed by power sharing control loops.

This paper presents a detailed modeling and control design as well as an accurate robust stability analysis for HPCSs used by residential dc microgrids. The proposed control strategy employs an inductive virtual impedance loop to effectively damp the low-frequency power/current oscillations. The frequencies of the oscillations are usually lower than 300 rad/s (50 Hz) depending on the parameters of dc microgrid.

The damping factor and frequency of oscillations are obtained using Mesh analysis approach. The overall dc microgrid is controlled based on a decentralized control strategy, i.e., each HPCS is individually controlled by a

multifunctional control scheme. The SC energy storage systems are used to improve the transient response of the fuel cell (FC) stack and the PV modules. The proposed HPCS controller consists of a multi-loop voltage controller for regulating the microgrid voltage, and a virtual impedance loop for power management. The virtual inductive impedance loop (dynamic droop gain) improves the dynamic performance of the power sharing control unit. Finally, the performance of the dc microgrid is evaluated using hardware-in-the-loop (HIL) simulations carried out in OPALRT technologies. The HIL results confirm that the proposed control strategy effectively damps the low-frequency power oscillations, and properly performs power management among the energy sources and the storage units.

Fig. 1. Schematic diagram of DC microgrid consisting of four DG units.



2. PROPOSED SYSTEM MODEL

Fig. 2 represents the general structure of a typical hybrid PV panel, battery, rectifier bridge unit used to provide an almost constant dc-bus voltage for residential dc microgrids. The PV stack and the battery module are, respectively, connected to the dc microgrid through a unidirectional and a bidirectional dc/dc buck converter. The battery, as a fast and short term discharge ESS, plays an effective role for proper functionality of its corresponding DG unit in terms of power quality and reliability, particularly for the sensitive loads. The dc/dc converters are used to regulate the output voltage of each DG unit at the desired dc-link value, while providing a smooth output current. A PV system operating under maximum power point tracking (MPPT) conditions helps to minimize the use of the battery module.

Fig.1 shows the overall structure of the residential dc microgrid comprising four DGs, as labeled by DG₁, DG₂, DG₃ and DG₄. The first two units consist of an FC module working in parallel with an SC and a PV system. DG₃ is composed of an FC module equipped with an SC module, while DG₄ is a single PV system.

The main objectives of the HPCS control system are as follows;

- (i) voltage control of the dc microgrid,
- (ii) power management among the energy resources and the ESS of each single HPCS unit,
- (iii) power sharing among all DG (HPCS) units to improve the dynamic performance of the dc microgrid. The controller

of the FC converter is designed to regulate the hydrogen flow and the current of the FC module. In addition, the converter of the PV system is controlled such that the maximum power point tracking operating condition is fulfilled.

Fig. 2 shows the block diagram of the proposed control system employed by the buck converter. The control system consists of a voltage control unit, and a current sharing unit. The purpose of the voltage control unit is to regulate the voltage at each bus using a double-loop control system. The outer and the inner loops are used to control the output voltage and current, respectively. The reference value of the voltage controller is determined by the current sharing unit. As shown in Fig. 3, the current sharing unit is developed using a virtual impedance loop. The design procedure of the aforementioned units will be explained in the following subsections. It should be noted that the proposed strategy for power oscillations damping can be applied to any type of dc/dc converter with arbitrary topologies.

3. OPERATING PRINCIPLE OF THE PROPOSED MODEL

The voltage controller unit includes a proportional integral controller as the outer loop and a positive gain (K_c) as the inner loop. The inner loop is incorporated to increase the internal stability of the voltage controller loop and to protect the switches of the SC module converter against over current. Furthermore, the inner loop decreases the output impedance of the converter. The gain K_c is determined such that the damping factor and the overshoot of the dominant poles of the inner loop become 0.7 and 5%, respectively. To eliminate the impact of the load dynamics, a feed forward controller is added in the voltage control loop. The controller parameters of the outer loop are determined according to the desirable stability margins and appropriate bandwidth. To attain good robust stability margin, excellent noise immunity and fast transient response, a phase margin of 19 degrees and a bandwidth of 2 kHz are considered for the voltage controller.

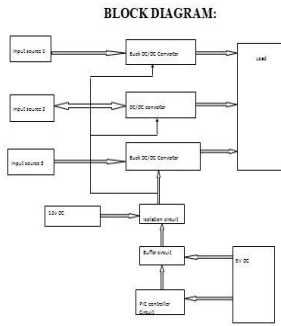


FIG 2 BLOCK DIAGRAM OF PROPOSED MODEL

The output of the closed-loop system can be expressed as $V_{out}(s) = H(s)V^*(s) - Z_{s0}(s)I_{sc}(s)$,

where $V_{out}(s)$ and $I_{sc}(s)$ are the output voltage and output current and the transfer functions $H(s)$ and $Z_{s0}(s)$ are obtained as

The reference signal of the voltage loop, i.e., $V^*(s)$, is determined by the current sharing control unit.

4. The Virtual Impedance Loop activity

The use of LPF provides the voltage control loop with a ripple-free reference signal (V^*), which in turn results in a high quality voltage regulation. The high-frequency oscillations (ripples) imposed to the DG output currents are due to the switching ripples of the converter, power electronic-based loads, or even the oscillatory currents produced by some types of dc loads. The cutoff frequency of the LPF is determined to eliminate the imposed ripples. It will be shown that the value of f_c has a significant effect on the low-frequency oscillations of DG output power. The averaged current is then applied to the current sharing controller whose output is the reference signal of the voltage control loop. To achieve active damping of the low-frequency oscillations of DG output power, the following V-I droop function is proposed:

$$V^*(s) = V_0(s) - (R_D + sL_D)I_{avg}(s),$$

where $V_0(s)$ is the nominal voltage of the dc microgrid, R_D and L_D are the static and dynamic droop gains, and $I_{avg}(s)$ is the output of LPF.

It should be noted that the conventional droop control strategy does not include any dynamic droop gain, i.e., L_D is zero. The static droop gain (R_D) is defined such that the output impedance which is implemented by a virtual impedance loop. To obtain L_D , first the characteristic equation of the current sharing unit will be derived. The output voltage of the DG units can be calculated as:

$$V_{out}(s) = H(s)V_0(s) - Z_{s0}(s)I_{sc}(s) - [Z_{RD}(s) + Z_{LD}(s)]I_{out}(s),$$

where $Z_{RD}(s)$ and $Z_{LD}(s)$ denote the output impedances of the HCPS units and are obtained in terms of the static and dynamic droop gains as follows:

$$I_{out}(s) = I_{sc}(s) + I_{pv}(s) + I_{FC}(s).$$

$H(s)V_0(s)$ and $Z_{s0}(s)$ are the voltage source and the output impedance of the SC converter, respectively, and the FC and PV systems have been modeled by two parallel current sources characterized by low transient responses.

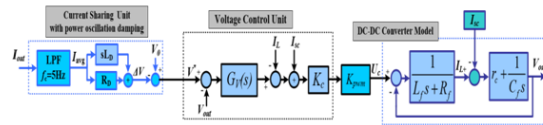


Fig 3 Virtual impedance loop activity diagram

Moreover, the local load of each DG is modeled by a parallel resistance R_{load} . The line resistance and inductance are respectively denoted by R_{Line} and L_{Line} which are unknown parameters, i.e., they may vary about their nominal values. $V_g(s)$ represents the Thevenin voltage of the rest parts of dc microgrid and its dynamic significantly depends on the dynamic behavior of the other DG

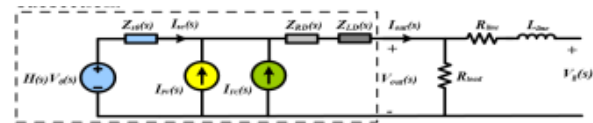


Fig 4

In fig 4 the impact of the load resistance and line impedance on the low-frequency modes of the DG unit can be studied based on where

$$Z_{out}(s) = Z_{s0}(s) + Z_{RD}(s) + Z_{LD}(s).$$

The frequency of dominant low-frequency modes of DG₁ is between 110 to 150 rad/s when the line resistance increases and, accordingly, the stability margin of the system improves. Theoretically, we can increase the line resistance to obtain an appropriate damping factor required for the stable operation of the microgrid. However, the increase of the line resistance is not always a practical solution as it increases the line losses and degrades the voltage profile. As observed, the system with a higher line inductance presents a better damping factor. As already discussed, the dynamic droop gain (L_D) is included to the current sharing controller to overcome the stability problem and to efficiently damp the low-frequency modes of the dc microgrid. The loci of the dominant low-frequency modes of DG₁, DG₂ and DG₃ for different values of L_D are shown in Fig. 8 (R_{Line} is assumed to be zero for all DG units). The dynamic droop gain L_D associated with a specified static gain R_D is tuned such that the damping factor and the overshoot of the system become 0.7 and 5%, respectively. It

should be noted that the dynamic droop gain L_D is adjusted for the worst operational condition, i.e., $R_{Line}=0$. Table II shows the controller coefficients designed for the DG units. It is to be noted that during design procedure of L_D for each DG unit, dynamics of the rest of dc microgrid are ignored, i.e., $V_g(s)$ in Fig. 5 is assumed constant. However, it will be shown that the damping factor of the overall dc microgrid will be very close to the desired damping factor of 0.7.

The dominant low-frequency modes of DG_1 when the cutoff frequency (f_c) of the LPF of the current sharing unit increases from 1 to 20 Hz, $R_{Line}=0.0125$ pu, and $R_{load}=1.15 \Omega$. The analysis is performed for DG_1 for the two cases of conventional droop and the proposed control system. The results show that the cutoff frequency of the LPF has a significant effect on the damping factor and frequency of oscillations. It should be noted that although the increase in f_c improves the damping factor of the system, to eliminate the high-frequency ripples and oscillations of the DG unit output current, f_c should be kept less than 10 Hz.

5. Low-Frequency Stability Analysis

A small signal analysis for the overall dc microgrid of Fig. 2, the linear models of all DG units including the lines and loads are obtained in the Laplace domain, as shown in Fig. 12, where $Z_{out}(s)=Z_{s0}(s)+Z_{RD}(s)+Z_{LD}(s)$ for each HPCS. The dominant low-frequency modes of the dc microgrid can be determined using its characteristic equation.

The damping factor of the dominant low-frequency modes is 0.015 when the conventional droop method is in service, whereas it is 0.774 ($DF=0.774$) when the proposed control system is used. It can be simply verified that the damping factor of the overall dc microgrid will be higher than 0.7 when the dynamic droop gain of each individual DG unit is adjusted such that its damping factor becomes 0.7. Fig. 13 also shows that the frequency of the dominant low-frequency modes is about 226 rad/s (36 Hz) when the DG units use the conventional droop controller. It is to be noted that the dominant low-frequency modes of the overall dc microgrid can not be determined by separately analyzing each single DG system.

5.1 ROBUST STABILITY ANALYSIS

A robust stability analysis is carried out to obtain a robustness margin for the uncertain parameters of dc microgrid. The characteristic equation of the closed-loop DG system, includes the load and line parameters which are uncertain. In particular, the line and the load resistances (R_{line} and R_{load}) significantly vary about their nominal values, and thus affect robust stability and the dominant low-frequency modes of each closed-loop DG unit. On the other hand, the parameters of voltage controller, static droop gains, capacitor of buck converter, K_{PWM} , and LPF parameters are almost fixed or have very small variations. Therefore, we can

assume that the parameters with small variations have no impact on the robust stability. the two parameters R_{line} and R_{load} are the main sources of uncertainties in DG model. The robustness margin is a region in the space of parameters in which the closed-loop system remains stable.

SIMULATIONS RESULT VALUES

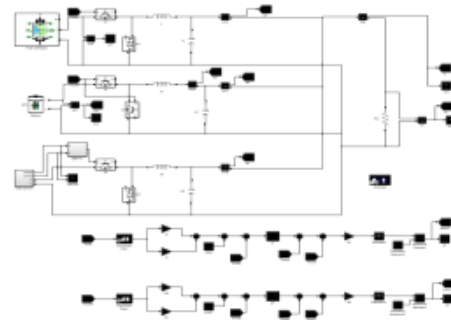


Fig 5. circuit model of the overall dc microgrid for mesh analysis

The simulations are advantageous since they tackle the time inefficiency of the online simulations, and provide us with the possibility to make a sensitivity analysis on the system parameters. The dc microgrid is connected to the ac grid through an interlinking converter. The power flow of the IC is zero indicating that the microgrid is in an islanded mode of operation. DG_1 , DG_2 and DG_3 are considered as dispatchable DG units having the capability to contribute to the power management of the microgrid. DG_4 is a single PV system and is considered as a non-dispatchable source. In this study, the loads are considered as a constant-impedance load. Load #3 is a dc motor which is connected to the dc microgrid via a boost dc/dc converter. the proposed current sharing control method is employed to improve the transient response of the microgrid. Several load switchings are considered to verify the dynamic performance of the proposed control strategy has shown below diagram.

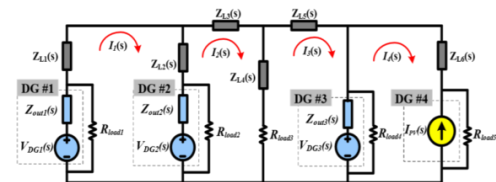


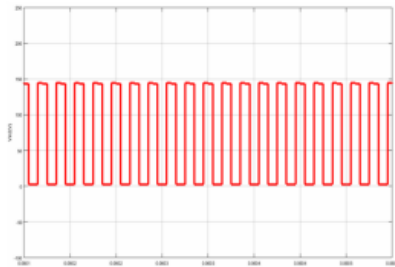
Fig 6

More specifically, the high-impedance line refers to the case in which the resistance of the microgrid lines are ten times higher than those of the low-impedance lines listed in to further accentuate the efficiency of the proposed method, the real-time simulations are repeated for the conventional

droop strategy. It should be noted that DG_4 is non dispatchable and cannot contribute to the microgrid power sharing. Similarly, for the second load change (stepwise load decrease), the dynamic response of the DG units when the conventional droop is used for microgrid characterized by both low and high-impedance lines are respectively as observed, for the case of low-impedance line, when the conventional droop strategy is used, the output currents of the dispatchable DG units are oscillatory due the small damping factor (0.015) of the dominant low-frequency modes of the system. However, for the same load step-down and for the case of high-impedance lines, the current oscillations are significantly damped due to the high damping factor

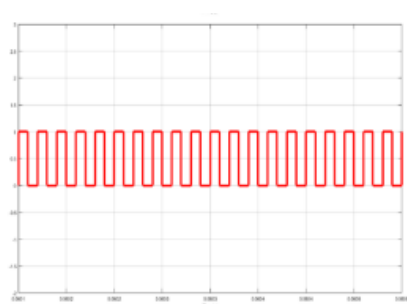
characteristics of the lines ($DF=0.612$). Nevertheless, the high damping factor does not merely guarantee the appropriate current sharing among the units as shown. Moreover, the use of inductive virtual impedance loop can effectively damp the unwanted oscillations in the HPCS units' output currents, while providing an appropriate current sharing among the dispatchable units. To achieve this goal, each unit decreases its current by drifting its reference voltage according to its V-I droop curve.

THE INPUT VALUE FROM BATTERY



6. SIMULATION RESULTS

THE OUTPUT VOLTAGE & CURRENT

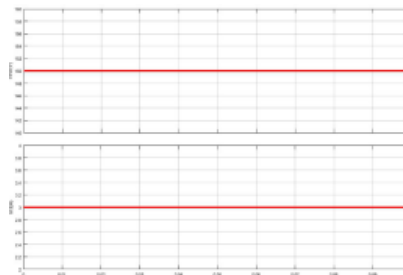


However, for the same load step-down and for the case of high-impedance lines, the current oscillations are significantly damped due to the high damping factor characteristics of the lines ($DF=0.612$). Moreover, the use of inductive virtual impedance loop can effectively damp the unwanted oscillations in the HPCS units' output currents, while providing an appropriate current sharing among the dispatchable units. To achieve this goal, each unit decreases its current by drifting its reference voltage according to its V-I droop curve. To further evaluate the performance of the proposed control strategy, similar load step-up, for the case

of low-impedance lines with and without proposed virtual inductive loop, are applied at $t=12$ s.

The output currents of the PV modules remain constant. In fact, the PV system of each individual DG unit only contributes to provide a portion of the base demanded load, while each DG unit participates in the power sharing

THE INPUT FROM THE PV PANEL



according to the proposed current sharing strategy. To achieve this goal, at $t=12$ s, the FC module of each DG unit increases its output power to follow the reference current produced by the FC current controller, while the SC module of each DG unit compensates the shortage between the power of the FC system and the demanded load power. The FC system increases its output power at a limited response rate. It is to be noted that the SC modules will be in standby state when the FC modules successfully provide the demanded load power

7. CONCLUSION

The proposed system involves a to regulate the microgrid voltage, and a virtual impedance loop to carry out efficient power management. battery energy storage is used to compensate the slow transient response of the rectifier. It is shown that the low-frequency modes of microgrid are

implemented by the power management controllers. To actively damp the low-frequency current sharing modes, a virtual inductive impedance loop is proposed. The proposed control strategy can simply be applied to other types of dc/dc converters with different topologies (e.g., isolated and non-isolated). In this paper, based on the guardian map theorem, a robust stability analysis is also carried out to determine the robustness margin for the uncertain parameters of microgrid.

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