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***Abstract*—Centralized or decentralized secondary controller is commonly employed to regulate the voltage drop raised by the primary controller. However, in the case of high capacity MGs and long feeders with much voltage drop on the line resistances, the conventional methods may not guarantee the voltage regulation on the load busses within a suitable range. Therefore, in addition to compensate the voltage drop of the primary controller, it is necessary to regulate the voltage of critical loads. In this paper, a new voltage regulation strategy is proposed to regulate the voltage of Micro-Grid (MG) by employing the average voltage of identified critical busses, which are determined by the proposed modal analysis. Numerical steady state analysis and preliminary simulation results validate effectiveness of the proposed scheme. Furthermore, experimental results are performed to demonstrate the viability of the proposed approach.**

Keywords— dc microgrid, droop control, modal analysis, secondary controller, voltage regulation.

I. Introduction

The concept of ac/dc MicroGrids (MGs) has been proposed in recent years to increase reliability, power quality, decrease losses and pollution in the distribution power systems [1], [2]. Furthermore, dc MGs are more applicable, reliable and efficient systems to integrate many power sources and loads, such as photovoltaic arrays, fuel cell units, battery storages, motor driven loads, and full converter based generators such as micro-turbines and wind turbines, which naturally have a dc coupling.

In order to have a stable operation in a dc MG, appropriate load sharing controller, and voltage regulators are required. Droop based primary controller has been applied to dc MGs to properly control the load sharing and improve the stability of the MG. However, voltage based droop methods suffer from poor voltage regulation and load sharing [3]–[8]. Considering large line resistances in the case of long feeders, the performance of the droop methods is not satisfactory. To increase the accuracy of the load sharing, large droop gains should be employed at the primary level. Larger droop gains cause higher voltage drop in the case of dynamically stable operation [7]–[11]. The secondary control approach has been carried out to compensate the voltage drop due to the droop method. Secondary regulators can be implemented with either a centralized or a decentralized control policy [8], [11]–[15]. In both cases, the secondary controller should regulate the dc voltage of the MG. In centralized schemes, the voltage of localized loads connected to a common bus or the voltage at the coupling point into the utility grid should be regulated [9], [10]. On the other hand, in decentralized methods, the average voltage of generator busses (busses with voltage source converter), is controlled [6], [7], [10]–[12], [16]

In the centralized secondary approach, it is considered the loads are localized at a common buss and the secondary controller regulates the voltage of the common bus at a reference value. A central control unit measures the voltage of common buss and send the set point voltage to the voltage controlled converters [8]–[10]. Since the reliability and resiliency of the system in the presence of a central controller is questionable due to the communicating among converters and the central control unit, some distributed methods are presented [8], [11]. In the distributed approach, the secondary controllers are implemented in the control system of each converter. The voltage or voltages of some busses are communicated among the converters. The secondary control of each converter regulates the average voltage of these busses [6], [8], [12]. Furthermore, in order to improve the system resiliency and reliability, a consensus protocol based secondary approaches are presented in [11], [17], where only the voltage of generation busses are communicating among the converters. Furthermore, a frequency droop based approach is also presented in [7], [16] in which the average voltage of generation busses can be properly regulated without utilizing any communication system.

Furthermore, dc voltage in the dc MG is a local variable and voltage variation due to the feeder resistances at different points of MG is necessary in order to control the current flow. Therefore, the output voltage of the converters cannot be regulated at a reference value, and hence, the voltage of converters may be higher or lower than the reference voltage value. For instance, the voltage drop over the feeder connected to the converter with lower output voltage causes more voltage deviation at the end of that feeder. In the conventional secondary approach, short feeders and localized loads on a common bus or only on generator busses are considered. However, in practice, the loads are not localized at one bus or at generator busses, and the feeders may be long and voltage drop over the line resistances is noticeable. Considering real conditions for an MG, conventional secondary controllers cannot guarantee the voltage regulation on load busses. Notably, the voltage of critical loads has to be regulated to remain in an acceptable range. Meanwhile, the dc MGs mostly include Constant Power Loads (CPLs) [18], which may affect voltage regulation, since decreasing voltage increases the current and can consequently lead to a higher voltage drop in the lines.

One approach to overcome the aforementioned issues is to design wires with lower resistance to reduce the effect of voltage drop. This can be a suitable solution in short feeders and low capacity MGs. However, in the case of long feeders and high capacity MGs, it may not be an economical solution. A feasible solution can be regulating the critical buses rather than controlling all buses. However, the challenge is to have a suitable methodology in identifying critical busses. Modal sensitivity analysis are presented in [19] to find the critical busses through an ac grid, where the voltage of critical busses can be regulated by injecting reactive power. This approach is modified and applied to the dc MGs, where the voltage of busses are related to the dc currents. Hence, the critical busses can be found by employing the modified modal sensitivity analysis.

In this paper, modal analysis based approach is proposed to determine the critical busses in the dc MG [20]. Furthermore, a secondary controller regulates the average voltage of weak busses in a dc MG by the secondary controller to improve the voltage regulation through the MG. In section II, the proposed modal sensitivity analysis is explained to identify the critical or weak busses in the dc MG. Furthermore, in Section III and IV, the steady state numerical analysis and simulations are presented to illustrate the effectiveness of the proposed approach in comparison with the conventional methods. In addition, the experimental results are given in Section V. Finally, the outcome of this paper is summarized in Section VI.

II. Modal Analysis

According to [19], the variation of ac voltage of different busses in an ac grid can be calculated by sensitivity analysis. In this method, Prof. Kundur suggests a modal sensitivity based approach in order to determine critical busses in the ac grids. In the ac grids, the voltage of different busses are related to the reactive power. Therefore, the critical busses can be determined by the sensitivity of corresponding voltage to the reactive power variation in different busses. Since the voltage of one bus can be affected by the injected reactive power in different busses, to find the critical busses, modal analysis is employed. In this method, modal voltages are defined which are directly related to the reactive power variation in that mode. Moreover, participation of the reactive power of different busses in the voltage of one mode can be calculated by participation factor matrix. In the following, the modified modal sensitivity analysis is given in order to determine the critical busses in dc MGs.

Droop schemes have been employed to control the load sharing among dispatchable energy units in dc MGs [10], [21]–[23]. Droop controlled converters in dc MGs can be modeled as an ideal voltage source in series with a droop resistance [22], [23]. Fig. 1 shows a typical dc bus with droop-controlled Distributed Generators (DGs), constant power converters such as photovoltaic arrays, local loads, and feeders connected to other busses. Here, the constant power source is modeled as an ideal current source [24].

According to electric circuit theory, applying Kirchhoff's Current Low (KCL) on i^{th} bus shown in Fig. 1 results in (1), with I_{si} being the current of constant power source, I_{pi} being the current of local load, V_{ref} is the rated voltage, g_{di} is the inverse of the droop gain, V is the bus voltage, indices of i and j refer to the i^{th} and j^{th} busses, and g_{ij} is the conductance of the feeder between i^{th} and j^{th} busses.

$$I_{si} = I_{Pi} + \sum_{\substack{j=1 \\ j\neq i}}^{n} g_{ij}(V_i - V_j) + g_{di}(V_i - V_{ref}) \qquad (1)$$

According to [8], [9], the droop gain of i^{th} converter can be defined proportional to the corresponding rated currents as:

$$g_{di} \propto I_{rated,i} \qquad (2)$$

where $I_{rated,i}$ is the rated current of i^{th}. Furthermore, the droop gains are selected to satisfy the system dynamic stability [8], [9]. However, the system stability analysis is out of scope of this paper.

In practice, constant power sources like PV and wind have very slow dynamic response due to the slow variation of climate condition. Therefore, in this paper, constant power sources are considered as a current source. However, in case, if they have fast dynamic response, they can be modeled like CPLs.

The load power and current can be modeled as (3) [25], where P_o is the load power when the terminal voltage of load, V, is equal to the rated value V_o, and α is a coefficient to model the load behavior. For CPL, $\alpha = 0$, for Constant Current Load (CCL), $\alpha = 1$, and for Constant Impedance Load (CIL), $\alpha = 2$.

$$P = P_o\left(\frac{V}{V_o}\right)^{\alpha}; \qquad I_{Pi} = P_o\frac{V^{\alpha-1}}{V_o^{\alpha}} \qquad (3)$$

Applying (1) to all busses of the MG, the KCL equations can be rearranged in the matrix form as (4), where $I_s = [I_{s1}, I_{s2}, \ldots, I_{sn}]^T$, $I_P = [I_{P1}, I_{P2}, \ldots, I_{Pn}]^T$, G is the n×n conductance matrix of MG, which can be calculated as (5), G_d is a diagonal matrix which includes the droop conductance of the droop controlled converters, which can be calculated as (6), and n is the total number of busses.

$$I_s = I_P + GV - G_dV_{ref} \qquad (4)$$

$$G = [\,a_{ij}\,]_{n\times n}; \quad a_{ii} = \sum_{j=1}^{n}(g_{ij}) + g_{di}; \quad \underset{k=1:n,k\neq i}{a_{ik}} = -g_{ik} \qquad (5)$$

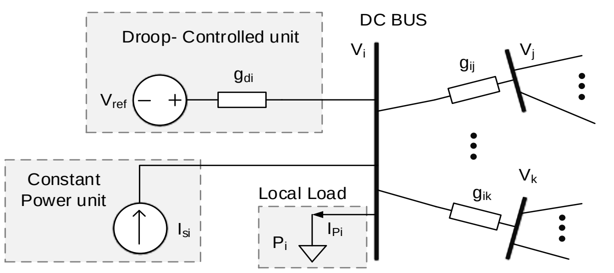

Fig. 1. Single line diagram of a typical bus in dc MG.

$$G_d = diag(g_{d1}, g_{d2}, ..., g_{dn}) \quad (6)$$

The linear form of (4) can be obtained as (7), where J is the Jacobian matrix of the system, and G_p is a diagonal matrix which contains the incremental conductance of the loads defined by (8). The effect of increasing or decreasing of current at one bus ΔI_s, on the voltage of different busses can be determined by the Jacobian matrix of the system.

$$\Delta I_s = G_P \Delta V + G\Delta V = (G_P + G)\Delta V = J\Delta V; \quad J \equiv G_P + G \quad (7)$$

$$G_P = diag(g_{P1}, g_{P2}, ..., g_{Pn}); \quad g_{Pi} = (\alpha - 1)P_o \frac{V^{\alpha-2}}{V_o^{\alpha}} \quad (8)$$

The Jacobian matrix can be converted into the diagonal form by the right and left eigenvalue matrices. This relation is shown in (9), where ξ is the right eigenvalue matrix, η is the left eigenvalue matrix and Λ is a diagonal matrix containing the eigenvalues of J.

$$J = \xi \Lambda \eta; \quad \Lambda = diag(\lambda_1, \lambda_2, ..., \lambda_n); \quad \lambda_1 \le \lambda_2 \le ... \le \lambda_n \quad (9)$$

Equation (7) can be rearranged as (10). For a symmetric Jacobian matrix, $\xi^{-1} = \eta$. Hence, by defining $i = \eta \Delta I_s$ and $v = \eta \Delta V$, as the vector of modal current variation and modal voltage variation, equation (10) can be rewritten as (11).

$$\Delta I_s = J\Delta V = \xi \Lambda \eta \Delta V \quad (10)$$

$$i = \Lambda v \quad (11)$$

In modal representation, k^{th} modal voltage is only related to the k^{th} modal current by the k^{th} eigenvalue (λ_k) as defined in (12).

$$v_k = \frac{1}{\lambda_k} i_k \quad (12)$$

Therefore, the k^{th} eigenvalue shows the sensitivity of the k^{th} modal voltage to the k^{th} modal current. Considering a small λ_k, the small modal-current injection or absorption, caused by large modal-voltage. Hence, the smallest λ_k determines the weakest mode. The contribution of the different busses at a desired mode can be determined by a participation matrix (P). The elements of participation matrix, $P_{ki,}$ show the participation factor of the k^{th} bus at the i^{th} mode, and can be calculated as:

$$P_{ki} = \xi_{ki} \eta_{ik} \quad (13)$$

Therefore, employing modal analysis determines the weakest mode and the weakest busses can be found by the bus participation matrix.

III. Numerical Analysis

In order to study the effectiveness of the proposed secondary controller, a typical dc MG is considered and modal analysis is used to identify the weakest busses in the MG. Without losing generality, as shown in Fig. 2, a simplified dc MG with two DGs is considered and distributed loads are connected to the MG by corresponding feeders. Two droop controlled DGs are connected to the first and fourth busses, and the droop conductance $g_{d1} = g_{d2} = 0.5\ \Omega^{-1}$. The MG can be connected to the utility grid at the second bus. The grid interface converter is modeled as a dc source, however, it can be controlled like droop based DGs. In this paper, the MG is assumed to be disconnected from the main grid. Therefore, busses one and four are responsible to regulate the dc voltage. The information of DGs/loads and lines are given in Fig. 2 and TABLE II. Two case studies with long feeders and short feeders are considered. In this study, the loads are considered to be CPL.

Following the presented modal analysis, the smallest eigenvalue of the system can be found as $\lambda_1 = 0.094$, $\lambda_1 = 0.106$ for Case I and Case II respectively. Participation factors of different busses at weakest mode (smallest eigenvalue) are given in TABLE III. At Case I with long feeders, the third bus has the highest contribution in the weakest mode. The fifth bus has also a high participation factor after the third bus. However, in the case of short feeders, the participation factors of different busses are close together. In short feeders the resistance of lines and voltage drop on the lines are small, hence, the differences in voltage levels will be small. Here the following approaches, which employ different voltage regulation schemes, have been considered:

- Approach I: regulating the average voltage of generator busses [6], [10], [11], V_1, V_4 in Fig. 2,
- Approach II: regulating the voltage of Point of Common Coupling (PCC) into the main grid [9], [10], V_2 in Fig. 2,
- Approach III: regulating the average voltage of total busses, V_1, V_2, …, V_5 in Fig. 2, and
- Approach IV (proposed approach): regulating the average voltage of the weakest busses, V_3, V_5 in Fig. 2.

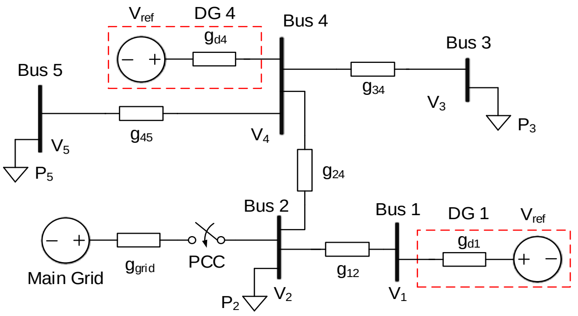

Fig. 2. Single line diagram of a typical dc MG.

TABLE I: DG and Load information for steady state analysis.

DG/Load	Capacity (kW)	Type
DG 1 Rated Power	40	Droop Controlled
P 2	20	CPL
P 3	30	CPL
DG 4 Rated Power	40	Droop Controlled
P 5	20	CPL

TABLE II: Line information for steady state analysis.

From Bus	To Bus	Resistance (Ω/km) [26]	Distance (km) Case I	Distance (km) Case II
Bus 1	Bus 2	0.65	0.5	0.5/3
Bus 2	Bus 4	0.65	0.5	0.5/3
Bus 3	Bus 4	0.65	0.5	0.5/3
Bus 4	Bus 5	0.65	0.25	0.25/3

TABLE III: PARTICIPATION FACTOR OF BUSSES AT WEAKEST MODE.

Bus	Participation Factor Case I: $\lambda_1 = 0.094$	Participation Factor Case II: $\lambda_1 = 0.106$	Bus Type
Bus 1	0.146	0.180	Droop
Bus 2	0.186	0.196	CPL
Bus 3	0.247	0.215	CPL
Bus 4	0.203	0.202	Droop
Bus 5	0.219	0.207	CPL

The effects of the different control approaches on voltage regulation are explained in the following.

Case I: in this case, long feeders for the diagram in Fig. 2 are considered. Normalized voltage of different busses based on rated voltage (400 V) is shown in Fig. 3 (a), in which they are calculated by the steady state load flow analysis. The violet graph shows the voltage of different busses in the case of regulating the voltage of PCC (i.e., the second bus). Using Approach I, the voltage of the third load bus is regulated at 90 % of the reference value. The blue graph shows the effect of regulating the global average voltage of the generator busses (Approach II). Applying this control method, the voltage of the third load bus is lower than 90 % and the fifth bus is lower than 95 %. Hence, this method cannot regulate the voltage of loads. The green graph shows the effect of regulating the voltage of all busses. This approach is better than regulating the voltage of one bus or regulating the voltage of generator bus. However, the voltage of the third load is lower than 95 %. Finally, the yellow graph illustrates the voltage of different busses in the case of regulating the voltage of the third and fifth busses, which have more contribution in the weakest mode. As it can be seen, in this approach, the voltage of loads can be properly regulated. The voltage of the third and fifth busses is between 95 % and 105 % and the voltage of the second bus is 105.9 %. According to the steady state analysis, the proposed method can effectively regulate the voltage of the load busses.

Case II: in the second case, the line feeders are considered to be one-third of the line feeders in Case I. Therefore, the line resistances and voltage drop will be small. The steady state analysis results are illustrated in Fig. 3 (b). As it can be seen, the voltage of load busses are regulated near the rated value with different regulation strategies.

The results of Case I and Case II confirm the applicability of the proposed modal analysis in identifying the weakest busses in dc MG and effectively regulating the voltage of load busses by secondary controller. In Case I, the participation factors of the two busses are higher than the others, hence, regulating the voltage of these busses guarantees an acceptable voltage regulation in load busses. However, in Case II, the participation of different busses are very close and load voltage regulation can be guaranteed with all regulation policies.

IV. SIMULATION RESULTS

A simplified dc MG shown in Fig. 2 is considered for simulations. The information of DGs, loads and lines is given in TABLE IV and TABLE V. Control block diagram of the boost converters for DGs is shown in Fig. 4, where $L_{dc} = 2\ mH$ and $C_{dc} = 500\ \mu F$.

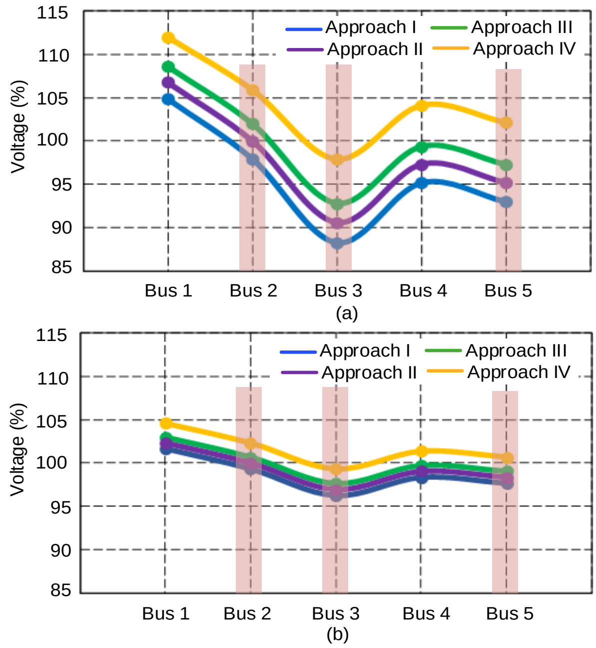

Fig. 3. Comparative numerical analysis of bus voltages with different control strategies – normalized by 400 V; (a) results of Case I with long feeders, (b) results of Case II with short feeders. Approach I: regulating average voltage of generator busses (V_1, V_4), Approach II: regulating voltage of PCC (V_2), Approach III: regulating average voltage of all busses, Approach IV: regulating average voltage of the weakest busses (V_3, V_5).

TABLE IV. DG AND LOAD INFORMATION FOR SIMULATION.

DG/Load	Capacity (kW)	Type
DG 1 Rated Power	5	Droop Controlled
P 2	2	CPL
P 3	3	CPL
DG 4 Rated Power	5	Droop Controlled
P 5	2	CPL

TABLE V. LINE INFORMATION FOR SIMULATION.

From Bus	To Bus	Resistance (Ω/m)	Distance (m) Case I	Distance (m) Case II
Bus 1	Bus 2	0.05	50	50/3
Bus 2	Bus 4	0.05	50	50/3
Bus 3	Bus 4	0.05	50	50/3
Bus 4	Bus 5	0.05	25	25/3

The inner current regulator is a PI controller with k_p = 0.1 and k_i = 2 and inner voltage regulator is a PI with k_p = 5 and k_i = 20. The droop conductance of DGs, $g_{d1} = g_{d2} = 0.1\ \Omega^{-1}$. A centralized secondary controller with k_p = 2 and k_i = 10 is considered to regulate the voltage of MG (V_{MG}). The four mentioned approaches are considered for voltage regulation of MG by the secondary controller including: (i) Approach I: average voltage of generator busses (V_1, V_4), (ii) Approach II: voltage of PCC (V_2), (iii) Approach III: average voltage of all busses, and (iv) Approach IV: average voltage of the weakest busses (V_3, V_5). Fig. 5 (a) and (b) show the simulation results for Case I with long feeders, and Case II with short feeders respectively. The effects of the secondary controller on the voltage regulation of MG with different approaches are illustrated in these figures as well.

Case I: as it can be seen in Fig. 5 (a), regulating the average voltage of generator busses, i.e., Approach I, results in the poorest voltage regulation, since V_3 and V_5 are lower than 95 %. Regulating the voltage of PCC, Approach II, is almost better than the Approach I, but it cannot still regulate the voltage of the load busses. Approach III can regulate the load busses, but it requires to communicate the voltage of all busses. The proposed approach, i.e., Approach IV, can properly regulate the voltage of the load busses. Therefore, using the voltage of the weakest busses as a feedback of secondary controller, can appropriately regulate the voltage of MG. In this approach, only the voltages of the weakest busses are required to be communicated, and hence, a suitable reliability can be obtained.

Case II: in the case of short feeders, as it can be seen in Fig. 5 (b), the voltage regulation with the proposed approach is better than the other approach. However, since the line resistances are small, the voltage variations are small, and consequently, all approaches can be used to regulate the voltage of MG. This result is already obtained from the modal analysis, where it is seen that in the short feeders, the participation factor of all busses are close together in the weakest mode.

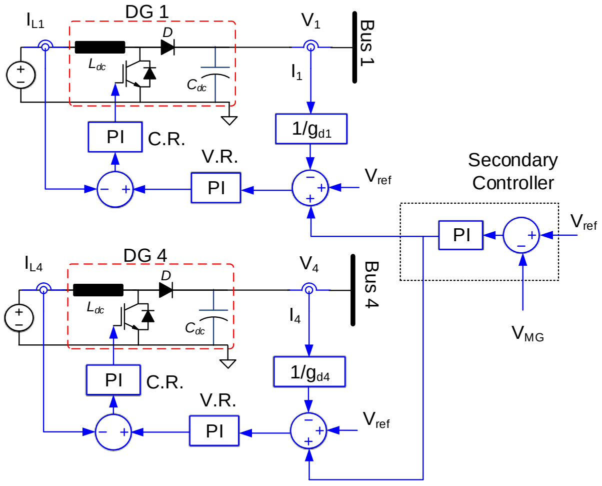

Fig. 4. Control block diagram of the converters in the MG shown in Fig. 2 – inner Current Regulator (C.R.), and inner Voltage Regulator (V.R.).

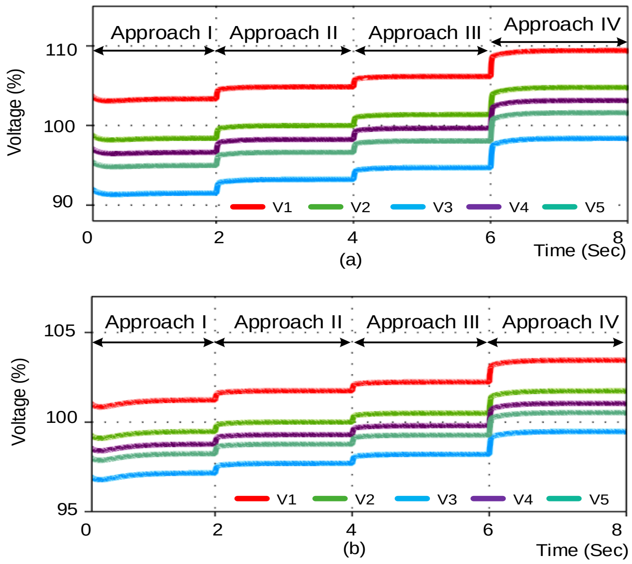

Fig. 5. Simulated normalized voltage of busses (based on 400 V): (a) considering long feeders (Case I), and (b) considering short feeders (Case II). Approach I: regulating average voltage of generator busses (V_1, V_4), Approach II: regulating voltage of PCC (V_2), Approach III: regulating average voltage of all busses, Approach IV: regulating average voltage of the weakest busses (V_3, V_5).

V. Experimental Results

In order to demonstrate the effect of the secondary controller on the regulation of the load voltage, experimental tests with a simple low voltage dc MG like the one shown in Fig. 2 are carried out. A photograph of the implemented hardware is shown in Fig. 6, and the hardware and control parameters are given in TABLE VI. The hardware setup includes two dc/dc boost converter with L_{dc} = 2 mH and C_{dc} = 560 μF, two resistive loads and one CPL (a single phase inverter connected to Bus 3). The dc link voltage is 100 V. The line impedances are also given in TABLE VII. A central controller – digital signal processor TI F28335 – is used to control the converters as well as to regulate the voltages as a secondary controller. The voltage of different busses are measured and sent to the central controller. The effect of the different secondary approaches on the voltage of the load busses are demonstrated in the following.

The experimental result of applying the secondary control Approach I is shown in Fig. 7(a). In this approach, the average voltage of generating busses is regulated at 100 V. As it can be seen from Fig. 7, the voltage drop of Bus 3 and Bus 5 are higher than 5%. Applying the Approach II, the voltage of bus 2 is regulated at 100 V, and the voltage of bus 3 is lower than 95 V, and hence the voltage drop is more than 5%.

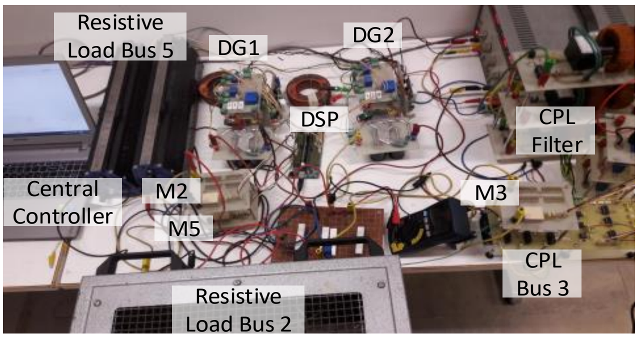

Fig. 6. Photograph of the simplified dc MG, including two dc-dc boost converters, V_{in} = 70 V, V_{out} = 100 V – M2, M3, amd M5 voltage measurement of Load 2, 3, and 5.

TABLE VI. Implemented Test Setup Parameters

Parameter	Values
DC link voltage	100
Converter parameters (L_{dc}, C_{dc})	2 mH, 560 μF
Voltage regulator (PI)	0.1 + 0.2/s
Voltage regulator (PI)	0.02 + 0.1/s
Droop gains	5, 5
Secondary regulator	0.12 + 0.2/s
Load at Bus 2 (Resistive)	200 W
Load at Bus 3 (CPL)	300 W
Load at Bus 5 (Resistive)	200 W

TABLE VII. Line Information for Experimental Tests.

From Bus	To Bus	Resistance (Ω)
Bus 1	Bus 2	2.2
Bus 2	Bus 4	1.7
Bus 3	Bus 4	1.7
Bus 4	Bus 5	1.2

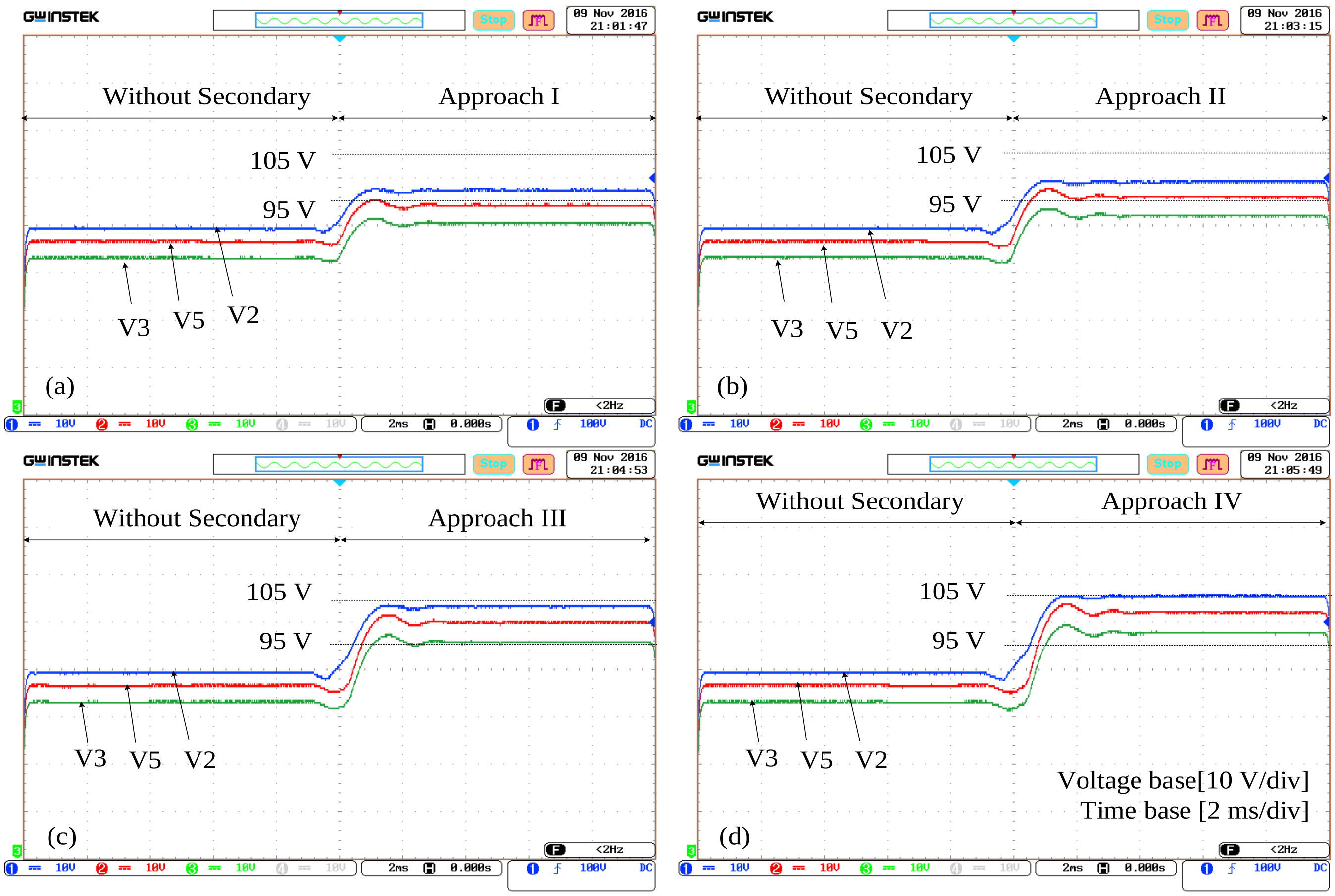

Fig. 7. Experimental results, secondary voltage regulation based on: (a) approach I, (b) approach II, (c) approach III, (d) approach IV. [10V/div], Time base [2 ms/div].

The experimental results of Approach III is shown in Fig. 7(c) implying suitable voltage regulation. However, in this case, three voltage sensors are required to monitor to load voltages. Furthermore, applying the proposed approach based on regulating the weak busses causes the suitable voltage regulation at the load busses as shown in Fig. 7(d), where the voltage of load busses are within 95 and 105 *V*, i.e., ± 5% voltage variation, which shows an acceptable voltage regulation.

VI. Conclusion and Discussion

There are three secondary control approaches in order to regulate the voltage of dc MGs including:

- Regulating the average voltage of generating busses,
- Regulating the voltage of PCC at the grid connection point
- Regulating the average voltage of all busses.

The first approach is the most common regulation method. However, it cannot guarantee suitable voltage regulation in the load busses. Furthermore, in some approaches, only the voltage of PCC is regulated, and it is considered the load of system is localized at PCC which is not practical. Furthermore, regulating the PCC voltage cannot guarantee acceptable voltage regulation in other busses. In order to have an appropriate voltage regulation through the MG, it is better to regulate the average voltage of all busses. However, measuring and regulating the voltage of all busses are not economical and may affect the system reliability. Therefore, the conventional secondary approaches cannot properly regulate the load voltages in the case of long feeders and distributed loads, which are much probable to see in practice.

In order to overcome the aforementioned issues, in this paper, a modal based sensitivity analysis has been introduced to find the weakest busses in the MG, and regulate the average voltage of them by the secondary controller. Regulating the voltage of the weakest busses results in an acceptable load voltage regulation by only communicating the voltage of a few busses. Meanwhile, in the case of short feeders, all control strategies can regulate the load voltages, since the voltage drop on the lines are negligible. This concept is also confirmed by the proposed modal analysis, where for short feeders, the participation factor of all busses are close together, and consequently, employing different secondary controllers can properly regulate the voltage of the loads.

The proposed approach is verified through steady state analysis and simulations. A scaled down test setup is used and tests are performed to demonstrate the viability of the proposed secondary control approach. Both simulations and experimental results show that the voltage of critical busses can be properly regulated by employing the proposed approach, where the conventional approaches cannot guarantee acceptable voltage regulation. Therefore, by utilizing the proposed secondary control, acceptable voltage regulation can be obtained through the dc MG.

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