IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 1, 2021, accepted June 9, 2021, date of publication June 14, 2021, date of current version June 23, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3089325

Improved Dynamic Response of DC Microgrid Under Transient Condition Using Inertia by Virtual Generation

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This work was supported by Science and Engineering Research Board (SERB), Government of India, under Project IMP/2018/000179.

ABSTRACT This article proposes new control architecture to improve the dynamic performance of DC microgrid by enhancing system inertia. The DC microgrids are gaining more importance due to the controlled and combined operation of multiple distributed energy resources (DERs). The DC microgrid is dominated by controlled power electronics converters. These converters are not having inbuilt inertia like rotating generators. Therefore, the DC microgrid has a fast rate of change of bus voltage under fluctuations of load, change in available power capacity of sources due to their randomness, etc. This affects the voltage profile and stability of the system under dynamic variation. The proposed closed loop control scheme estimates the amount of inertia required in the DC microgrid to minimize the voltage variation. The new power references are given to sources based on virtual generation to improve the inertia in the system. The proposed control scheme maintains the stability of DC microgrid. It also achieves effective power management based on available power in DERs with a minimum burden on the energy storage system (ESS). The bus voltages are regulated at reference value. The stability analysis of the system is carried out for DC microgrid under different operating conditions. The proposed control method is tested experimentally under diverse operating conditions.

INDEX TERMS DC microgrid, inertia, power management, transient stability, virtual generation.

I. INTRODUCTION

An effective way to reduce the energy crisis and carbon emission is possible by renewable energy sources (RESs) and distributed generations. The RESs with controlled power electronics converter gives the control over the intermittent nature of sources. An effective way to integrate these RESs, the microgrid provides a better solution. The DC microgrid is having advantages such as a direct interface with RES as most of them are DC in nature, higher conversion efficiency, less complex control, etc [1], [2]. The main challenges in the control of microgrid arise from the stochastic nature of RESs such as, solar and wind due to variation in power generation, uncertainties in load demands and schedules, and distributed topology of power sources that are spatially scattered due to location and size constraints [3], [4].

The microgrid consists of power electronics converters which are static devices and they did not store any kinetic energy like rotating devices. Thus, under the transient condition, there could be a large variation in bus voltage. If the bus voltage crosses its threshold limit, the microgrid becomes unstable and it may stop functioning if appropriate action is not initiated. Hence, under transient conditions due to the intermittent nature of RESs, dynamic fluctuations, etc. the sources are unable to supply additional power or absorb power from the system. This sudden supply and absorption of power is termed as inertia. The inertia is low in the DC microgrid as compared to the conventional grid as most of the devices are static in nature. This reduces the stability of the DC microgrid and also affects the power management in the DC microgrid [5].

The associate editor coordinating the review of this manuscript and approving it for publication was Alon Kuperman.

A. STATE OF THE ART

The state of the art is discussed for the low inertia problem in the DC microgrid. The initial inertia in DC microgrid under dynamic conditions is provided by the filter capacitor. Therefore, by increasing the capacity of the capacitor, the inertia could be improved. However, because of the low power density of electrolytic capacitor, short life span, large size, and increased cost, it is not recommended to adopt this solution. The super-capacitor is used to provide transient support to the system bus voltage under dynamic conditions. The super-capacitor is interfaced with the bus by a controlled converter. This reduces the transient response of the super-capacitor. It also increases the cost and complexity of the control scheme [6].

The inertia could be generated by supplying additional power to the system. Therefore, it is desirable to enhance the inertia of the DC microgrid by adequate power control of a controlled voltage source converter (VSC). The primary objective is to emphasized power control to include inertia. In grid connected mode [7], [8], the inertia is supplied by the utility grid. The grid connected VSC is controlled as a synchronous generator to generate the inertial response. However, this inertial response is only possible in grid connected mode. In standalone mode, the VSC could not provide the inertia, and hence, the system stability decreases. In standalone mode, the bus voltage is maintained by VSC. In a DC microgrid, the inertia is provided by a voltage source. In [9], [10], the inertia could be achieved by controlling a bidirectional converter with an energy storage system (ESS), super capacitor, or other microgrids. In this case, the dynamic behavior of control and sudden changes in the operational mode of the interfacing converter creates deviation in DC bus voltage with large voltage spikes [11]–[13]. The ESSs in electrical vehicles are used to provide inertia in transient conditions [14]. This increases the burden on the ESS and voltage source.

In droop control, the inertia is provided by all the sources simultaneously, as all the sources in droop control are voltage sources. In [15], [16], inertia is supplied by managing power sharing among sources. In [17], [18], a power sharing between sources with improved inertia is proposed for the DC microgrid. These methods are affected by large bus voltage regulation and circulating currents based on loading condition. The sources with controlled converters are operated to emulate the generator characteristics [19]. The inertial constant estimation is required to emulate the generator inertia. The damping performance of DC microgrid is addressed with negative feedback control technique to improve the inertia of system [20]. However, the DC microgrid consists of nonlinear elements, stochastic sources that affect inertia and power management. The interlink converters are utilized to provide inertia support in combined AC and DC microgrid [21]. In [22], a solar photovoltaic source with a battery bank is used to provide inertia. The battery is used as a reserve source for inertia. The stability of the system with droop control and with virtual inertia droop control is given in [23]. A coordinated control method is developed in [24] for adaptive virtual inertia in AC/DC microgrid. In [25] the droop based power sharing among the sources is modified for disturbance in generation as well in load. In [26], droop control with current feed forward control is developed for dynamic response. It utilizes different observers to operated droop control. A disturbance observer based method is given in [27] for inertia improvement. In [28], the estimation of inertia in AC microgrid is determined. However, in these methods an extra source, reserve ESS, or load curtailment is required to provide inertia. Thus, it affects the power management in microgrid and increases the burden on voltage source and ESS.

In addition, both the methods master-slave and droop control are affected by the intermittent nature of RESs. Therefore to maintain or improve the stability of microgrid under transient conditions, it is necessary to deal with system inertia. The required inertia can be supplied by proper power management of virtual generation in the DC microgrid. In [29], the virtual generation based power management control method is proposed. The sudden variation of the power output of all sources reflects in voltage oscillations. Therefore, it is necessary to estimate the amount of inertia required to minimize voltage variation under dynamic conditions.

B. CONTRIBUTION OF THIS ARTICLE

This paper proposes a new control technique for estimation and addition of inertia in DC microgrid based on available power in the renewable sources. This added inertia is used to maintain the stability of DC microgrid under dynamic conditions. The key contribution points of proposed control scheme are summarized as follows:

i) The proposed control scheme estimates the virtual generation i.e unutilized available power in every source in the microgrid.
ii) It effectively utilizes virtual generation from each source to supply inertia in the system to improve dynamic performance in closed loop system.
iii) It estimates the amount of inertia to be submitted in the system to mitigate transient. It also calculate the necessary quantity of inertia from individual source based on available power in respective source.
iv) The proposed control scheme effectively utilized the virtual generation for maintaining the system stability. It does not require any extra circuit or component such as additional source, ESS, etc in the DC microgrid. It also avoids the load shedding.
v) The system bus voltage regulation of system is improved with better power management under diverse operating conditions.

This paper is structured as follows. The problem formulation is mentioned in Section II. The proposed methodology is discussed in Section III. The detailed experimental verification is given in Section IV followed by some concluding remarks in Section V.

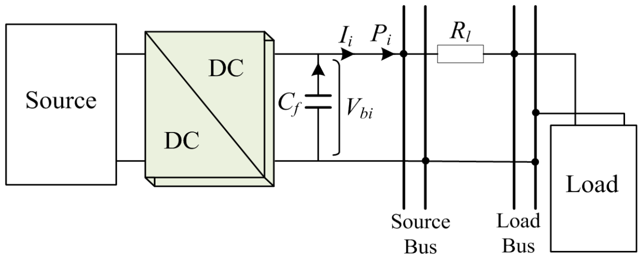

FIGURE 1. Controlled power electronics converter connected to bus.

II. LOW INERTIA PROBLEM IN DC MICROGRID

In the standalone DC microgrid, the voltage of the system is regulated by a voltage source. The prime role of a voltage source is to maintain voltage of system under different operating conditions by maintaining power balance in the microgrid. However, all the load fluctuations, transients, etc. are directly reflected on the voltage source. It affects the voltage regulation at every bus in the microgrid. The inertia of the utility grid reflects the capability of damping the frequency change, which is provided by the synchronous generator. Similarly, the inertia of DC grid is introduced to reflect the ability of damping voltage variation. Consider i^{th} source is connected to bus shown in Fig. 1. The power output (P_i) from this source is given as

$$P_i = V_{bi} I_i \tag{1}$$

where, V_{bi} is bus voltage and I_i is the output current from the source. Therefore, under transient condition,

$$P_i \pm \Delta P_i = V_{bi} I_i \pm \Delta V_{bi} \Delta I_i \tag{2}$$

where, ΔV_{bi} and ΔI_i are the variation in bus voltage and current. The transient is reflected as change in bus voltage variation. This transient power (ΔP_i) should be supplied suddenly to decrease the rate of change of bus voltage.

In DC microgrid, most of the sources are static due to power electronics converters. The filter capacitors in DC microgrid can prevent the DC voltage from sudden changes. When power fluctuates, capacitors can rapidly charge or discharge to mitigate the sudden change of bus voltages. Therefore, the transient power is supplied by filter capacitor. The additional power ΔP_{Ci} is provided by the capacitor,

$$\Delta P_{Ci} = V_{bi}\left(C_i \frac{dV_{bi}}{dt}\right) \tag{3}$$

where, C_i is the capacitance. The power supplied by a capacitor is limited by the actual capacity of capacitor. The inertia of the system can be enhanced by increasing the capacity of a capacitor or by inserting an additional capacitor. But, this increases the size and cost of system. Therefore, it is necessary to determine and supply the additional inertia under dynamic conditions by some other methods to regulate voltage and to maintain the stability of the DC microgrid.

III. PROPOSED METHODOLOGY

The inertia of system can be achieved by injecting additional power in the DC microgrid under contingency condition. The proposed control technique estimates the power references for controlled converters depend on sources, ESS, and load conditions to extract virtual generation as inertia and for better power management. These new references are based on various parameters. Let us consider, the microgrid consist of 'S' number of sources feeding to load demand (P_L). The power output of 'S' sources are given as $P_1, P_2, \ldots\ldots P_S$. The total load demand in the microgrid is P_L.

$$P_L = \sum_{i=1}^{S} P_i \tag{4}$$

From (4), the total load demand is supplied by 'S' sources and P_i is power output from individual source.

In conventional algorithms the average power is considered as reference power for individual source. The available power more than the rated power is not utilized. Therefore, the additional available power is termed as virtual generation and it is calculated as

$$\begin{aligned}\text{Virtual Generation} &= \text{Maximum available power generation} \\ &\quad -\text{average generation}\end{aligned}$$

$$P_{i.VG}(t) = P_{i.avi}(t) - P_{i.avg}(t) \tag{5}$$

where, $P_{i.VG}$ is the virtual generation of i^{th} source depends on available power ($P_{i.avi}$) in the individual source and average power generation ($P_{i.avg}$). It is depends upon environmental condition and time of the day. Therefore, additional power is never constant and it is dynamic in nature. This additional available power is used to supply the inertia in the DC microgrid. In similar way, the virtual generation in other sources is calculated and to supply inertia.

The proposed control technique estimates the power references for controlled converters depend on source and load conditions to include virtual generation as inertia and for proper power management. These new references are based on various parameters. In conventional methods, the average power is considered as reference power for individual sources. It is irrespective of the change in available power in renewable sources. In proposed method, the output power from individual sources is categorized into three different powers. The addition of these three different powers from individual sources defines the power reference for the converter [29]. It is expressed as

$$P_i = P_{i.\min} + P_{i\_R} + P_{i.VG} \tag{6}$$

where, $P_{i.min}$ represents the minimum power required to overcome converter losses and P_{i_R} is defined as the rated power of i^{th} source. $P_{i\cdot VG}$ reflects the virtual generation depends on available power in the individual source.

The power output of each source can change either due to deficiency or surplus of power available. Now, let us define P_i in relation to different indices for i^{th} source in the microgrid for minimum power, rated power, and virtual

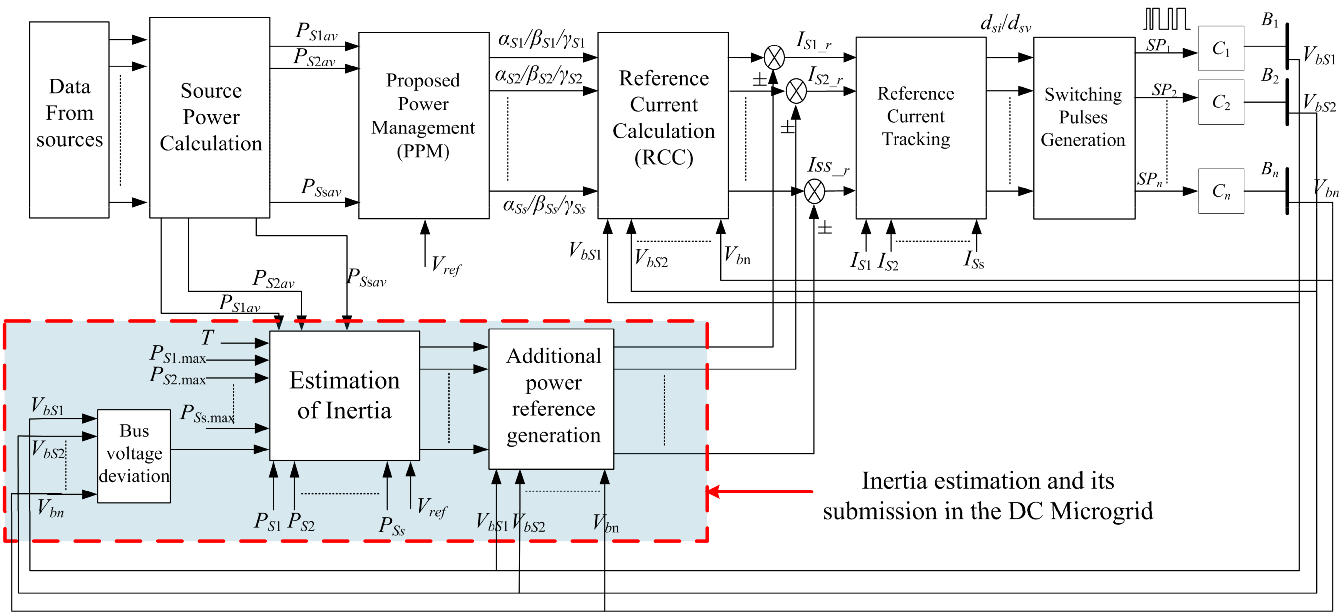

FIGURE 2. Block diagram of proposed control for inertia enhancement and power management control scheme.

generation. Therefore, the indices are defined to estimate the new reference P_i. It is expressed as

$$P_i = P_{i.\max}(\alpha_i + \beta_i + \gamma_i) \tag{7}$$

where, $P_{i.\max}$ is the maximum capacity of each source. α_i, β_i, and γ_i are the indices related to minimum power, rated power, and virtual generation respectively in the i^{th} source. The α_i is the index that represents the minimum power required from the source for operation of the converter. The respective converter comes into service only if the α_i reaches its optimal value i.e. $\alpha_{i.max}$. The index α_i is given as,

$$\alpha_i = \frac{P_{i.\min}}{P_{i.\max}} \tag{8}$$

The optimal value of α_i for i^{th} source is defined as $\alpha_{i.\max} = (P_{i.\min}/P_{i.\max})$.

The source provides power to load if available power in the source crosses the $P_{i.\min}$ limit i.e. the power above $P_{i.\min}$ is the useful power and it is varied in the operational power range. It is reflected in terms of index β_i. It is expressed as below

$$\beta_i = \frac{P_i - P_{i.\min}}{P_{i.\max}} \tag{9}$$

The maximum value for index β_i is expressed as $\beta_{i.\max} = (P_i - P_{i.\min})/P_{i.\max}$. The β_i comes into existence only if $\alpha_i \geq \alpha_{i.max}$. As soon as β_i exist, α_i becomes constant at its maximum value

The virtual generation corresponding to source is represented by index γ_i. The index γ_i exists only if the corresponding source has virtual generation. The γ_i indicates the surplus power available with the i^{th} source. It is expressed as

$$\gamma_i = \frac{(P_i - P_{i\_R})}{P_{i.\max}} \tag{10}$$

The maximum values of γ_i for i^{th} source are defined as $\gamma_{i.\max} = (P_{i.avi} - P_{i\_R})/(P_{i.\max} - P_{i\_R})$ respectively. The index γ_i appear only after $\beta_i = \beta_{i.max}$. Thus, the new current reference depends on change in power from the source, considering bus voltage V_{bi}, is given as

$$I_i = \frac{P_{i.\max}(\alpha_i + \beta_i + \gamma_i)}{V_{bi}} \tag{11}$$

This current reference depends upon the indices $\alpha_{i,}$ β_i, γ_i, and bus voltage. Thus, current reference changes depending on the availability of source power, bus voltage, load variation, and stress over the system (due to fault, stress on ESS, etc). Therefore, the power output from the source is classified in three terms, this is described below. The block diagram of proposed control is shown in Fig. 2.

a. Source Under no Performance: This is the condition when $\alpha_i < \alpha_{i.max}$, and implies that the respective source does not have sufficient power for its converter operation. However, the other parameters $\beta_i = \gamma_i = 0$, and the reference current under this condition is

$$I_{i.\min} = \frac{P_{i.\min}}{V_{bi}} = \frac{P_{i.\max}(\alpha_i)}{V_{bi}} \tag{12}$$

As soon as $\alpha_i = \alpha_{i.max}$, the interfacing converter delivers power to system. Therefore, with this minimum power the source function is shown in region R_1 of Fig. 3.

b. Source Under Normal Performance: This condition is possible only when $\alpha_i = \alpha_{i.max}$, $\gamma_i = 0$ and $0 \leq \beta_i \leq \beta_{i.max}$. The converter supplies power to load up to its predefined average value i.e. rated capacity. The reference current derived under this condition is given as

$$I_i = \frac{P_{i.\max}(\alpha_i + \beta_i)}{V_{bi}} \tag{13}$$

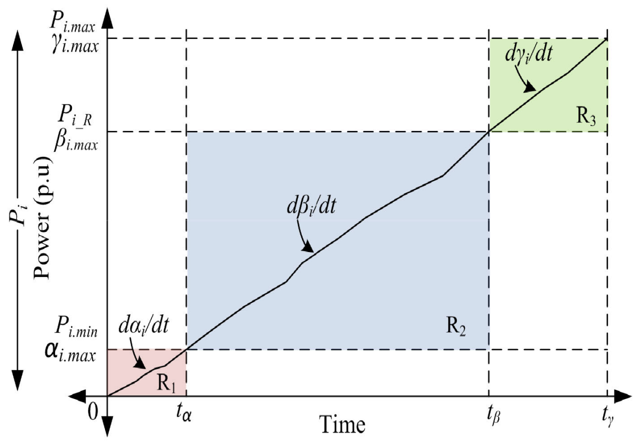

FIGURE 3. Parameters variation in accordance with power [29].

This power range is defined as the operational range of source region R_2 shown in Fig. 3.

c. Source Under Virtual Generation: In this condition i^{th} source should have available virtual generation. The new reference current obtained for this condition is expressed as

$$I_i = \frac{P_{i.\max}(\alpha_i + \beta_i + \gamma_i)}{V_{bi}} \tag{14}$$

It is possible to acquire this current when α_i and β_i are constant, these are set at their maximum limits and it is shown as region R_3 in Fig. 3. Three functional regions in terms of power availability from source with corresponding time are shown in Fig. 3. The change in power with respect to time provides dynamics of microgrid sources. The index γ estimates the virtual generation in individual source.

Now, this additional power (virtual generation) in the source is defined by index γ_i. It is based on available power in the source at any time interval. The required inertia provided by additional available power is estimated by proposed control method and virtual generation. The additional power in terms of virtual generation is expressed as,

$$\Delta P_{VGi} = P_{i.\max}\gamma_i \tag{15}$$

Thus, an additional power could be achieved by changing the power output from the source based on virtual generation. The magnitude of additional power is based on bus voltage deviation and available virtual generation in the source. The desired power change is achieved by controlling the current references considering the available virtual generation ($P_{i.\max}\gamma_i$).

A. ENHANCEMENT OF SYSTEM INERTIA

The controllable power source has ability to provide additional power (available virtual generation). This additional power could be utilized to enhance the system inertia. Therefore, the total inertial power is expressed as

$$\Delta P_i = \Delta P_{Ci} + \Delta P_{VGi} \tag{16}$$

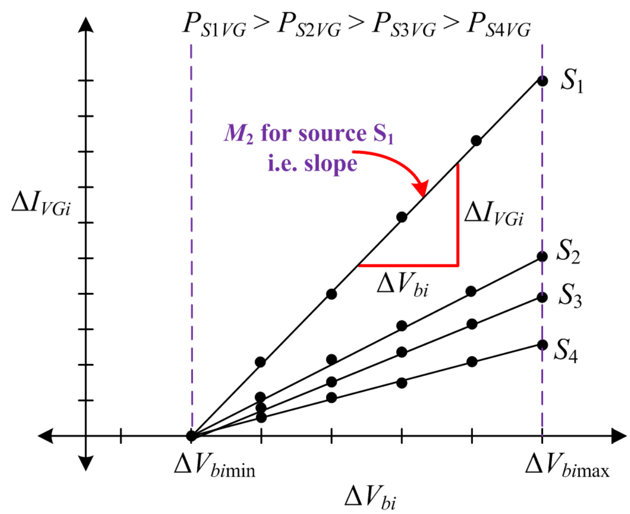

FIGURE 4. Constant M_2 for different sources.

where, ΔP_{VGi} is available virtual generation with i^{th} source. Now, the ΔP_{VGi} is expressed as

$$\Delta P_{VGi} = \Delta V_{bi}\Delta I_{VGi} \tag{17}$$

where, ΔV_{bi} is deviation in bus voltage and ΔI_{VGi} is incremental current because of virtual generation. Therefore in order to mitigate the bus voltage deviation additional power is supplied from virtual generation. If bus voltage deviation is large then the requirement of virtual generation is more. It is observed that,

$$\Delta V_{bi}\alpha\Delta I_{VGi} \tag{18}$$

Hence, (18) could be expressed as

$$\Delta P_{VGi}\alpha\Delta V_{bi}^2 \tag{19}$$

$$\Delta P_{VGi} = M\Delta V_{bi}^2 \tag{20}$$

where, $M = M_1.M_2$. The M_1 indicates the availability of virtual generation in i^{th} source. $M_1 = 1$ implies that, the virtual generation is available in the source and $M_1 = 0$ implies that virtual generation is not available in the source. The M_2 is proportional constant between ΔV_{bi} and ΔI_{VGi}. The value of M_2 differs for different sources. The different M_2 for various sources is shown in Fig. 4. The M_2 value depends on the capacity of the source. It is calculated as the slope between virtual generation and change in bus voltage.

The additional inertia could be provided by i^{th} source in terms of supplying virtual generation. Therefore, the total inertia provided by i^{th} source is combination of two inertias. At first stage the instant inertia is provided by capacitor and at second stage it is provided by the virtual generation (available additional power). Hence, the total inertia with capacitor and virtual generation is calculated by integrating (16) for time interval. Therefore, from (16) the total inertia supplied

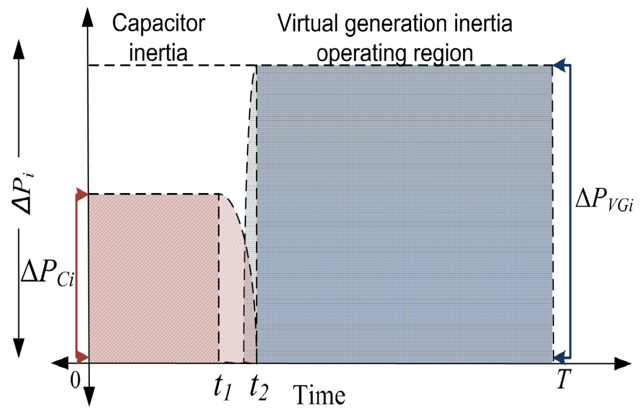

FIGURE 5. Inertia emulation region by capacitor and virtual generation.

by i^{th} source over a time T is given as

$$\int_0^T \Delta P_i dt = \int_0^T (\Delta P_{Ci} + \Delta P_{VGi}).dt \tag{21}$$

$$\int_0^T \Delta P_i dt = \int_0^T \left(V_{bi}\left(C_i \frac{dV_{bi}}{dt}\right) + M\Delta V_{bi}^2\right).dt \tag{22}$$

In (21), the inertia is supplied by capacitor over a period t_1 and from t_2 to T it is supplied by virtual generation in the source. The instant t_1 and t_2 are different as the virtual generation from the source could not be supplied without time delay. This is because of time required in converter operation. These time periods differs based on nature of transient. It is shown in the Fig. 5. The additional inertia is supplied by controlling power output from the individual source.

$$\Delta E_i = \int_0^{t_1} V_{bi} C_i dV_{bi} + \int_{t_2}^T M\Delta V_{bi}^2 dt \tag{23}$$

where, ΔE_i is inertia provided by i^{th} source. The initial inertia is provided by capacitor for time interval $(0 - t_1)$ and later it is provided by virtual generation (t_2 - T) of i^{th} source. The t_1 and t_2 depend on nature of transient and interfacing converter operating time.

$$\Delta E_i = \left[\frac{1}{2} C_i \Delta V_{bi}^2\right]_0^{t_1} + \left[M\Delta V_{bi}^2 \Delta t\right]_{t_2}^T \tag{24}$$

In order to improve the inertia, the available virtual power is estimated based on proposed control scheme is discussed in next subsection.

B. ADDITIONAL INERTIA ESTIMATION

The requirement of additional inertia in DC microgrid is based on deviation of bus voltage. This matching of inertia varies all the time and it depends on nature and time of transient. The inertia supplied by virtual generation should regulate the bus voltage. Thus, it is important to estimate amount of additional inertia to be extracted from virtual generation to regulate voltage.

From (21), the amount of additional inertia is estimated based on bus voltage deviation. The proposed method acquires voltage of every bus from the respective sensor. The bus voltage is measured (observed) at each time instant (K). In normal operating condition the voltage source maintain the microgrid voltage at defined level. The other sources supply power based of power references given by power management algorithm at defined voltage level. Whenever, there is transient in microgrid it affects the voltage. The proposed method calculates the voltage deviation (ΔV_{bi}) for bus at each time instant. The additional inertia is produced and injected subject to following condition.

$$\Delta V_{bi} > \Delta V_{b\min} \tag{25}$$

where, $\Delta V_{b\min}$ is minimum allowable voltage deviation in DC microgrid. If the constraint (25) is satisfied then there is requirement of inertia in the microgrid. For different time intervals the inertial parameters J_1 and J_2 are calculated as

$$J_1 = \frac{[V_{bi}(K) - V_{bi}(K-1)]}{T_S} \tag{26}$$

$$J_2 = \frac{[V_{bi}(K-1) - V_{bi}(K-2)]}{T_S} \tag{27}$$

where, T_S is sampling time.

Case i:

If, $(V_{bi}(K) - V_{bi}(K-1)) > \Delta V_{b\max}$ then, inject all available power in the system to boost up inertia. The $\Delta V_{b\max}$ is the maximum positive bus voltage deviation allowed in the microgrid. All the available virtual generation is injected in the system to supply inertia in the system.

Case ii:

If, $(V_{bi}(K) - V_{bi}(K-1)) < \Delta V_{b\max}$ then check J_1 and J_2 are of same nature i.e. either incremental or decremented then,

$$J' = \frac{J_1 + J_2}{2} \tag{28}$$

The proposed control scheme calculates the amount of inertia required by microgrid to mitigate the voltage deviation. The inertia parameters are calculated for time instant K, the proposed control estimate the voltage deviation for time instant $(K+1)$. It is expressed as

$$\Delta V_{biEst}(K+1) = \Delta V_{bi}(K) \pm J'(K) T_S \tag{29}$$

where, ΔV_{biEst} is estimated voltage deviation. It is used to calculate amount of inertia to be produced and supplied by using virtual generation. Thus, (25) is modified as

$$\Delta E_{iEst} = \left[\frac{1}{2} C_i \Delta V_{biEst}^2\right]_0^{t_1} + \left[M\Delta V_{biEst}^2 \Delta t\right]_{t_2}^T \tag{30}$$

where, ΔE_{iEst} is estimated inertia supplied by i^{th} source to restore the voltage deviation. The limits for V_{bi} are depend on (30) and it is given as,

$$\Delta V_{bi} \in [\Delta V_{b\min}, \Delta V_{b\max}] \tag{31}$$

The maximum inertia produced by i^{th} source is subject to condition of γ_i

$$\gamma_i \in (0, \ \gamma_{i\max}] \tag{32}$$

where, $\gamma_{i\max}$ is represent maximum virtual generation in i^{th} source. Additional power (ΔP_{VGi}) required for inertia is determined from (30). The total inertia is produced and supplied by additional power available in 'S' number of sources in the system. Therefore, the relation between inertia, voltage variation, and defined parameters of microgrid is expressed in terms of available additional power supplied by all the sources in the system. The aggregated inertia is expressed as,

$$\int_0^T \Delta P_T dt = \int_0^{t_1} \sum_{i=1}^{S} \Delta P_{Ci} dt + \int_{t_2}^{T} \sum_{i=1}^{S} \Delta P_{VGi} dt \tag{33}$$

$$\int_0^T \Delta P_T dt = \int_0^{t_1} \sum_{i=1}^{S} \Delta P_{Ci} dt + \int_{t_2}^{T} \sum_{i=1}^{S} P_{i.\max} \gamma_i dt \tag{34}$$

From (33) it is realized that the virtual generation in the sources is utilized to provide inertia in the microgrid. The total power under transient condition (ΔP_T) is supplied by a capacitor and available power in the various sources connected in the microgrid. This decreases stress on the voltage controlled source in the microgrid. The power sources are responsible not only for power management but also to maintain the stability of the microgrid by providing the required additional inertia.

At the initial stage, the proposed technique acquires all the input data from sensors and determines the different indices [25]. The system voltage is regulated by the voltage controller attached to the strongest source. The new reference current (I_{Si_r}) is computed by the current controller connected with the rest of the sources in reference current calculation (RCC). The additional inertial references are estimated and added to RCC with proposed power management (PPM). The block diagram of the proposed control technique is shown in Fig. 2. The available power in individual source is calculated based on sensor attached with respective source. The available power is used to estimate the indices for source. The index γ_i for i^{th} source is used to calculate available power for inertia. The proposed method calculates bus voltage deviation at each time instance based on the sensor attached to the bus. The bus voltage deviation also used to calculate inertial parameters J_1 and J_2. These inertial parameters are applied to calculate the inertia requirement to mitigate the bus voltage deviation at the next time instant. Based on inertia requirement and index γ_i, the power references are determined for respective sources. The power references are converted into current references with respective to bus voltages. Then, the old current references are replaced by new current references. The proposed control algorithm is given below,

Proposed Control Algorithm

Step 1: Initializations:

- Define number of sources, energy storage system (ESS), loads (critical and non-critical) in DC microgrid and their connectivity.
- Define sampling time, number of buses and interconnecting line resistances in the multibus DC microgrid.
- Define minimum, operational and maximum power ratings for sources and ESS. Define power rating and the priorities for critical and non-critical loads. Define the nominal bus voltage reference for DC microgrid.

Start:

[1] Read all V and I data (bus voltages, power output from the sources, and available power in sources).
[2] Calculate initial values of indices α, β, γ for each source in the system from (8), (9), and (10) respectively.
[3] Check bus voltages and calculate rate of change of bus voltage for given sampling time. If $(V_{ref} - V_{bi}) = 0$, then (Connect non-critical load if disconnected previously).
[4] If $(V_{bi}(K)\text{-}V_{bi}(K-1)) > \Delta V_{b\max}$ then, inject all virtual generation from each source in the system to boost up inertia. Go to step 8.
[5] If, $(V_{bi}(K)\text{-}V_{bi}(K-1)) < \Delta V_{b\max}$ then, calculate bus voltage deviation and the calculate the inertial parameters J_1 and J_2 from (26) and (27) respectively.
[6] If bus voltage deviation and rate of change of bus voltage is more than threshold value then, then estimate the required amount of inertia by (30).
[7] Calculate the power references for individual source based on inertia requirement and available virtual generation in the source (based on index γ).
[8] If power output of each source reaches to maximum then curtail the noncritical load based on defined priority.
[9] Go to step 1.

C. SYSTEM STABILITY

The effectiveness of proposed methodology is verified by analyzing the stability of the DC microgrid. A dual loop control strategy is employed with inner current loop and outer voltage loop to regulate system bus voltage under dynamic conditions. The block diagram of designed controller is shown in Fig. 6. The small signal model is shown in Fig. 7. The H_v(s) and H_i(s) are the voltage and current sensor gains respectively. The reference voltage V_{ref} is compared with actual measured bus voltage by voltage sensor. The output signal is given as $H_v(s)V_{bi}(s)$. The objective is to maintain $H_v(s)V_{bi}(s)$ equal to V_{ref}, so that bus voltage (V_{bi}) accurately follows V_{ref} in spite of the disturbance to regulate microgrid voltage. The H_{si} and H_{sv} are the control signal given by the proposed control scheme. The proportional integral (PI)

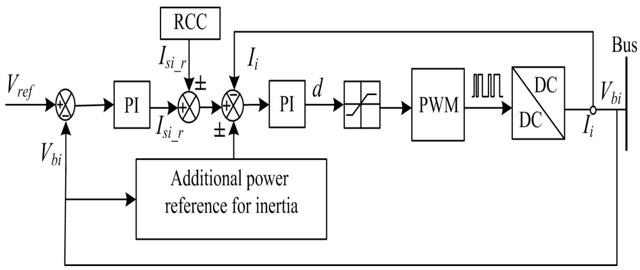

FIGURE 6. Block diagram reference current tracking.

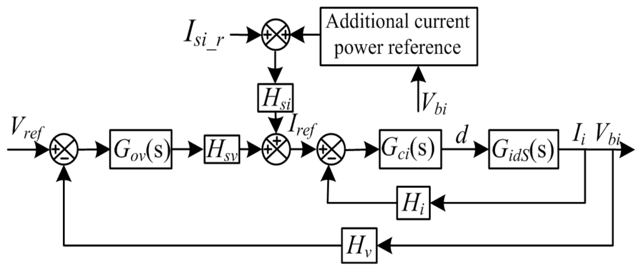

FIGURE 7. A small signal model block diagram of simplified controller with proposed control method.

compensators (G_{ov} and G_{ci}) are designed to increase the low frequency gain. The prime control objective is that the bus voltage should be maintained near to reference value and at frequency well below the loop crossover frequency. The new reference current to the controller is estimated by the RCC in the proposed method.

The main objective of the proposed control scheme is to regulate the DC bus voltage within defined range by providing inertia under dynamic conditions. Based on available power in the sources, the dynamic behavior of DC bus is governed by the available additional power in the source. This is achieved with the developed control technique which provides appropriate power references to the controller of interfacing converters. The converter has to follow the new power reference estimated by the proposed control technique under diverse conditions. The open loop transfer function (G_{ol}) of current loop considering small signal model of a converter shown in Fig. 7 is given as

$$G_{ol} = G_{ci}(s)G_{id}(d)H_i(s) \tag{35}$$

where, $G_{ci}(s) = (K_{pI} + K_{iI}/s)$ is transfer function of PI controller with K_{pI} and K_{iI} are controller gains, $G_{id}(s)$ is a transfer function of converter and H_i(s) is feedback sensor gain. The closed loop transfer function (G_{cl}) of current loop is given as

$$G_{cl} = \frac{G_{ci}(s)G_{id}(d)H_{si}}{1 + G_{ci}(s)G_{id}(d)H_i(s)} \tag{36}$$

The controlled converter regulates system bus voltage and the closed loop transfer function (G_{cl}) is derived as

$$G_{cl} = \frac{G_{ov}(s)G_{ci}(s)G_{id}(d)H_{sv}}{1 + G_{ov}(s)G_{ci}(s)G_{id}(d)H_i(s)} \tag{37}$$

where, $G_{ov}(s)$ is PI controller transfer function with K_{pV} and K_{iV} are controller gains, H_{sv} is controller signal from the

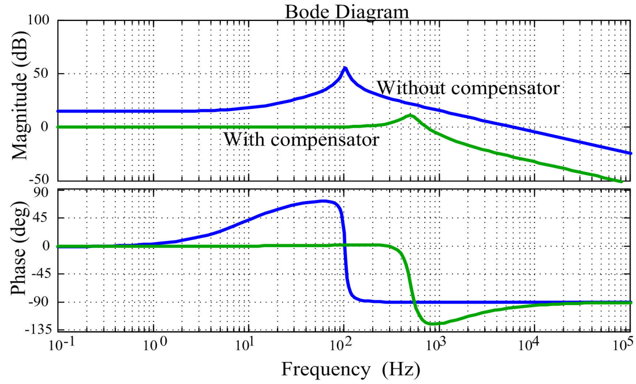

FIGURE 8. Bode plot of converter without and with controller.

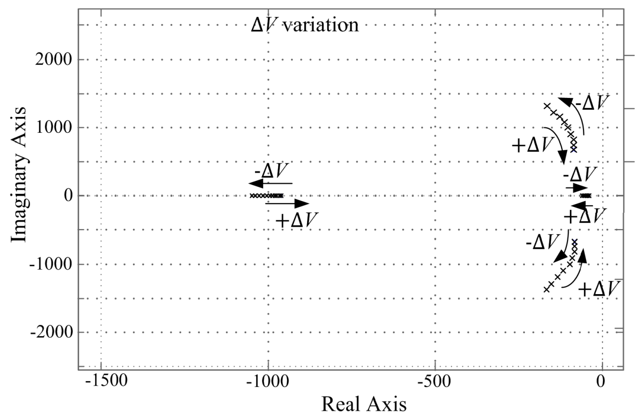

FIGURE 9. Closed loop poles for change in voltage reference.

proposed control scheme. The controller for the converter is designed to provide stable operation in defined limits of voltage variation. The proposed control scheme is tested on DC microgrid under different operating conditions.

The Bode plot of a developed converter without and with controller considering the reference by proposed control technique is illustrated in Fig. 8. The closed loop controller is designed such that the converter follows the power reference estimated by proposed control technique. The closed loop controller gain margin and phase margin of this control loop are infinity and 53.71° respectively. The Bode plot with compensator shows that the power reference is followed by the controller. The controller stability is also verified by analyzing poles movement under voltage variation shown in Fig. 9.

IV. RESULTS AND DISCUSSION

A 48 V standalone DC microgrid consist of 5 buses is developed to test the performance of proposed control scheme. It is illustrated in Fig. 10. It consists of two solar photovoltaic sources (S_1, S_2) with different power ratings and one ESS (battery). In the developed control method, the maximum voltage variation of load bus set as ± 5% of its reference voltage [3]. The sources, the ESS and loads (critical and non-critical) are connected to buses (B_1, B_2, B_3, B_4, B_5) by

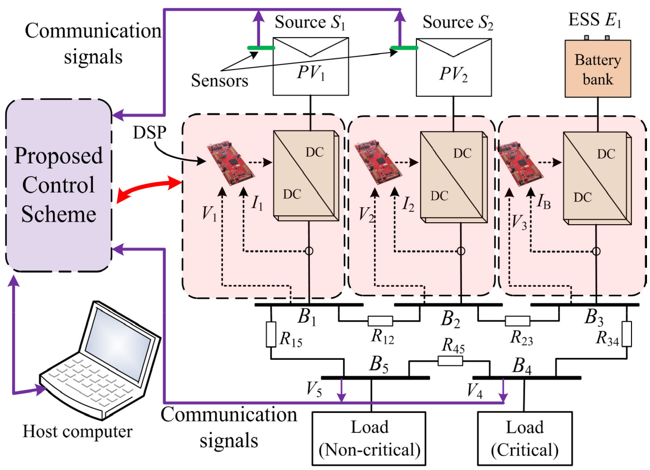

FIGURE 10. DC microgrid system under consideration.

controlled converters. The different buses are interconnected by lines to form different networks.

The lines resistances are given as R_{12}, R_{23}, …….R_{15}. The voltage and power controller is designed in DSP (TMS320F28379D) processor. The LEM voltage (LV25p) and current sensors (LA55a) are used and they are calibrated based on rating of the converters. A tracopower is used to provide the auxiliary supply to sensor and gate driver. The sampling time is taken as 30μsec. The DC microgrid parameters are given in Table 1. The proposed control technique is tested on different operating conditions of DC microgrid. Some of these conditions are discussed in this section as below.

A. CASE I

In this condition, the sudden load variation is considered. At the earlier stage, the microgrid is under normal operation source S_1 is operating as a voltage source and the total load demand is 1300 W. The total load demand is supplied by sources S_1 and S_2. The source S_1 is operating at 670 W and S_2 is operating at 430 W and the ESS is operating at 200 W. At $t = 2.4$ s, the load demand increases from 1300 W to 1450 W. The total dynamic changes are reflected on the voltage source. Therefore, the power supplied by source S_1 is changed to 820 W. The source S_2 and ESS are operating at 430 W and 200 W respectively.

The power variation is shown in Fig. 11 (a). The total variation is reflected on the voltage source. Therefore, the bus voltage changes from 47.87 V to 45.9V. Therefore, the system moves towards instability as the bus voltage is near to its lower limit. The bus voltage variation is shown in Fig. 11 (b).

However, with same power scenario, the load demand changes from 1300 W to 1450 W shown in Fig. 11 (c). The source S_2 is having virtual generation of 70 W and the ESS is having additional power capacity of 50W. This provides an additional inertia. Therefore, with the proposed control method modifies the power references of the sources.

TABLE 1. The DC microgrid system parameters.

Parameter	Symbol	Value
Source S_1 (max, rated, min) power	($P_{S1.max}$, $P_{S1.r}$, $P_{S1.min}$)	(850, 670, 30) W
Source S_2 (max, rated, min) power	($P_{S2.max}$, $P_{S2.r}$, $P_{S2.min}$)	(500, 430, 20) W
ESS (max, rated, min) power	($P_{ESS.max}$, $P_{ESS.r}$, $P_{ESS.min}$)	(250, 200, 20) W
Bus Voltage	V_b	48V
Line Resistances	[R_{12}, R_{15}, R_{23}, R_{45}, R_{34}]	[0.1, 0.2, 0.1, 0.07, 0.02]Ω
Load	P_L	(0-1480)W
Converter Parameters for Sources		
Inductor for filter	L	2.1mH
ESR of inductor	L_r	0.13 Ω
Capacitor for filter	C_f	2200μF
ESR of capacitor	C_{fr}	0.15 Ω
Switching frequency	F_s	40kHz
Converter Parameters for *ESS*		
Inductor for filter	L_{ESS}	1.5mH
ESR of inductor	L_{ESSr}	0.12 Ω
Capacitor for filter	C_{fESS}	2200μF
ESR of capacitor	C_{fESSr}	0.15 Ω

Thus, S_1 shares 750 W, source S_2 shares 500 W and ESS shares 200 W within 38ms. The power scenario is shown in Fig. 11 (c). As the inertia is provided by source S_2 hence, the bus voltage varies from 47.87 V to 47.3 V. The bus voltage is 45.9 V without proposed method. The bus voltage is shown in Fig. 11 (d) which is regulated within defined range.

B. CASE II

Initially the total load demand of 1300W is supplied by the source S_1, source S_2 and ESS as 680W, 430W and 200W respectively. The load changes at $t = 2.4$s from 1300W to 1480 W. The total load is reflected on voltage source S_1 hence, the source S_1 power output varies from 670 W to 850W. The source S_2 supplies 430W and ESS supplies 200W. The power variation is shown in Fig. 12 (a). The bus voltage changes to 45.6 V from 47.8 V shown in Fig. 12(b).

Now, the DC microgrid is on the verge of instability as the bus voltage is on the lower limit. As the source S_1 is operating at its maximum rated power capacity therefore, the system is on the verge of instability. However, with the proposed control scheme the inertia is provided by source S_2 and the ESS to support the voltage source. Therefore, for the load power changes from1300 W to 1480 W and to provide the inertia, the source S_1 power output changes from 680 W to 730 W, the source S_2 power output increases from 430 W to 500 W and ESS power output changes from 200 W to 250W within 41ms. The power variation is shown in Fig. 12 (c). The bus voltage is reduced to 45.6 V without proposed control method. The bus voltage changes from 47.8 V to 46.91 V with proposed control scheme shown in Fig. 12(d). Hence, the bus voltage is regulated under defined limits.

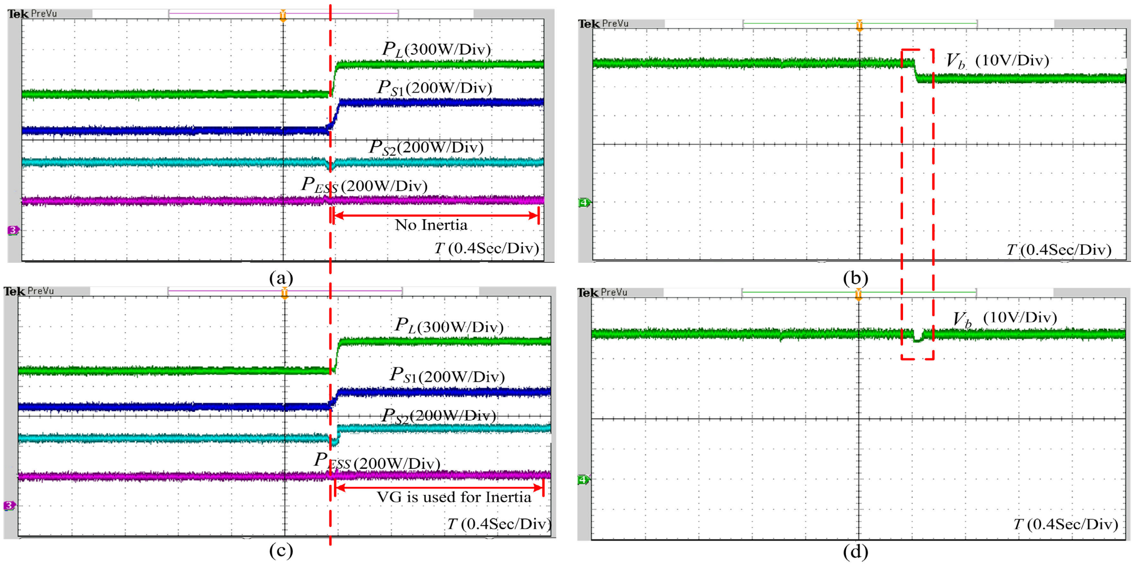

FIGURE 11. Performance evaluation under dynamic variation case I (a) power variation without inertia, (b) bus voltage without inertia, (c) power variation with supplied inertia, (d) bus voltage with supplied inertia by proposed control scheme.

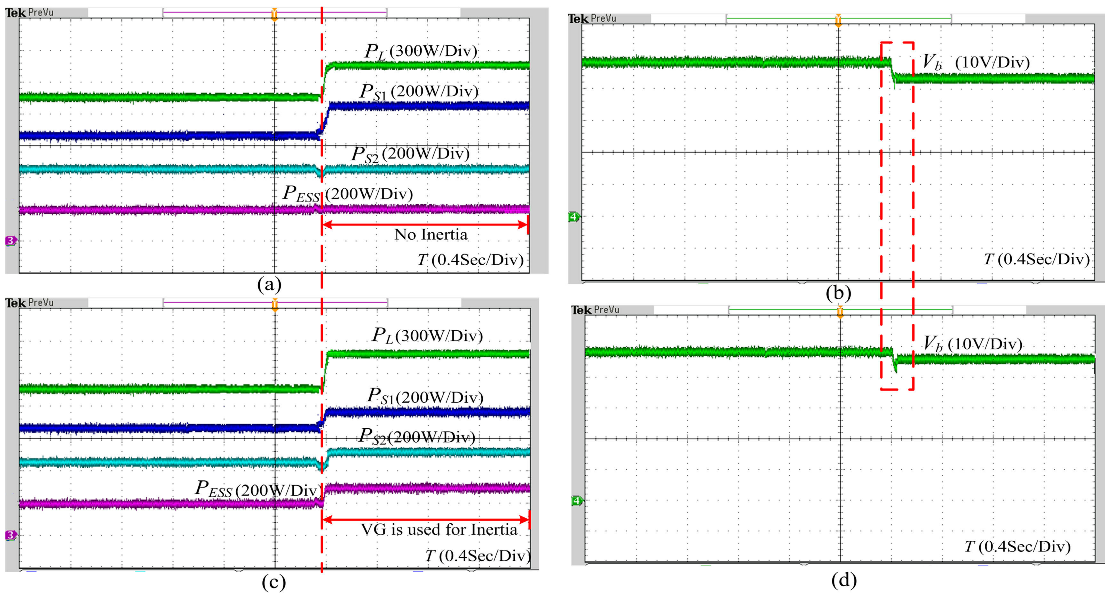

FIGURE 12. Performance evaluation under dynamic variation case II (a) power variation without inertia, (b) bus voltage without inertia, (c) power variation with supplied inertia (d) bus voltage with supplied inertia by proposed control scheme.

C. CASE III

In addition to case II without proposed control scheme, the voltage source is operating at its maximum available power. Therefore, for small load variation of 20W load demand the system becomes unstable as there is no inertia in the system. The unstable voltage is shown in Fig. 13. However, with the proposed control scheme the bus voltage is regulated at 46.8 V with same load variation of 20 W by providing additional inertia due availability of virtual generation of 20 W in 36ms.

The variation of eigenvalues over the change in available inertia is shown in Fig. 14. The eigenvalues plot for the proposed system by using inertia concerning available power. The dominant eigenvalues of the system travel towards the imaginary axis, as the transient and bus voltage regulation increases. The eigenvalues shifts away from the imaginary axis as the available additional power is used to provide inertia and to minimize bus voltage variation under dynamic conditions. However, if the requirement of inertia and bus voltage variation increases beyond limits (maximum available power) then, eigenvalues crosses the imaginary axis.

The proposed control method injects additional power within a small time interval termed inertia and it improves the bus voltage hence, the eigenvalues move away from the imaginary axis. Therefore, the proposed control method maintains system stability under dynamic conditions. The bus voltages

TABLE 2. Comparison of proposed method with different methods.

SN	Criterion	[13]	[15]	[16]	[17]	[22]	[23]	Proposed scheme
1	Effective power management	No	Yes	Yes	Yes	No	No	Improved
2	Additional space	Yes	No	Yes	Yes	Yes	Yes	No
3	Additional Cost	Yes	No	Yes	Yes	Yes	Yes	No
4	Load curtailment	Yes	Yes	No	No	No	No	No
5	Adaptive nature to source condition	No	Yes	No	No	No	No	Yes
6	Control scheme complexity	Moderate	Moderate	Less	More	More	More	Less

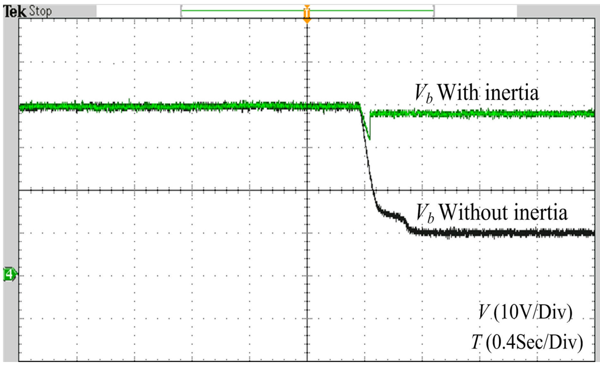

FIGURE 13. Case III load bus voltage variation with and without proposed control scheme for large transient on the system.

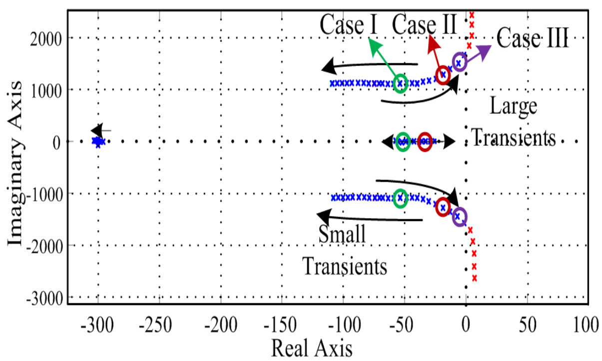

FIGURE 14. Eigen values plot with virtual generation for microgrid.

and available power for each bus and source are taken as observer parameters. All the information is available which gives more observers in comparison with [26], [27]. Therefore, the inertia is supplied in the microgrid whenever there is a transient on any bus in the microgrid. In the proposed method, the inertia control loop is operated with a power management scheme and does not require any additional control. Therefore, reduces the complexity and computational burden.

The DC microgrid bus voltage is regulated within a defined voltage deviation. The proposed control scheme also performs the power management within DC microgrid based on defined parameters. It estimates the virtual generation in the sources and used it effectively for stability enhancement. The bus voltage is regulated at its reference value by maintaining the power management in the system.

A detail comparison of the proposed control method with other methods is given in Table 2.

V. CONCLUSION

In this article, a new control technique is developed to improve the dynamic performance of DC microgrid under transient conditions. The requirement of additional inertia is estimated based on available virtual generation in the sources and nature of transient. The fast rate of change of bus voltage under fluctuations of load and intermitting nature of sources is minimized by the proposed control technique in the DC microgrid.

The proposed control scheme estimates the additional available power in the source by defined parameters and used this power to improve the system inertia. Therefore, the bus voltage is improved and the stability of the system is maintained under dynamic variation in the DC microgrid. The amount of inertia provided by the source and system is estimated by using the proposed control method. Hence, a large variation of bus voltage is minimized. The system bus voltage is regulated under a defined voltage range under various power scenarios. The key finding of this article are listed below:

1) The proposed method utilized virtual generation in individual sources effectively to supply inertia in the system. The proposed control method is closed loop system.
2) The amount of additional inertia requirement is estimated based on dynamic conditions and virtual generation in each source.
3) No extra circuit or component is required for additional inertia in the DC microgrid. Thus, the cost and size of the system is reduced. It also reduces the stress on the ESS and avoids the load shedding.
4) The bus voltage is regulated at reference value and the proposed control method achieved power management with minimum burden on ESS.

The stability analysis is carried out under different operating conditions. The proposed control technique is experimentally tested and verified with different conditions for standalone DC microgrid. In grid connected mode, the proposed control method could be used to provide local inertial support to the utility grid. However, the performance of the proposed controller needs to be closely analyzed under various nonlinearities in the system, nonlinear loads, fault at bus/line, and weak grid conditions. Therefore, a transient stability approach will be studied under various nonlinearities in the system. The inertia support could be provided to the utility grid or other microgrids under various economic dispatch constraints and conditions.

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