IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 4, 2021, accepted March 23, 2021, date of publication April 5, 2021, date of current version April 14, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3071029

A Comprehensive Investigation on High-Frequency Oscillation in DC Microgrid

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ABSTRACT This paper presents the small-signal stability performance of a dc microgrid (MG) and investigates the interactions between the converter controllers by studying the critical modes. A comprehensive small-signal analysis using both the impedance-based method and eigenvalue-based analysis method has been presented thoroughly to investigate the high-frequency oscillation in the dc MG. The results show that there are inherent weak modes within the dc MG which could destabilize the MG in the presence of disturbances. Moreover, the controller gains and dc-link capacitance are found to be the most sensitive to substantial disturbance and have a significant influence on the weak modes leading to oscillation and resonance. The source side converter is found to be more influential than the load side converter in regard to various disturbances.

INDEX TERMS DC microgrid, eigenvalue analysis, impedance analysis, power oscillation, resonance.

I. INTRODUCTION

Even though the first complete power system was commissioned in 1882, due to the difficulties of voltage scaling, the dc system was not considered as a transmission and distribution system until recently. With the advancement of power electronics converters and the capability of dc buses in integrated renewable resources, the dc system draws significant attention for transferring electrical energy over a long distance through high voltage dc (HVDC) systems to medium and low voltage dc MG distribution systems. [1]–[6].

The dc grid is a combination of multiple sources, including solar photovoltaic (PV), battery energy storage system, fuel cells, capacitors, and loads. The application of a dc MG can be realized in the commercial building, military center, EV charging station, educational institute, shipboard, remote, and rural areas. Besides, it can be a feasible solution for electrification during natural disasters and even reenergize the grid after a blackout. There are a number of advantages of the dc MG over the ac counterpart, such as the absence of reactive power, skin effect, angular and frequency instabilities [7].

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

Further, there is no issue with inrush current as there is no traditional transformer in case of dc MG [8]. On the other hand, in terms of economic prospects, dc MG is higher efficient, cost-effective, and reliable, compared to the ac MG [1]. Nevertheless, despite numerous advantages, understanding and minimizing power oscillation within dc MG remain a significant challenge over the past few years [9], [10].

The power oscillation in the dc MG can be generated due to various reasons, such as poorly designed controller, switching of lines, and sudden changes of load or generator output [9]–[11]. The output power of the dc MG comes mainly from distributed energy resources (DERs) such as the PV/ wind generator which is intermittent in nature and can create a significant impact, for instance, reduce or fluctuate the power on the dc bus. The disturbance is pervasive in the power system and can happen at any time in the source-side to load-side simultaneously. Further, the disturbances can lead to a power oscillation in the dc system with a drastic consequence. It can severely weaken or destroy the devices, do physical damage to assets due to adverse interactions, and compromise system security [12], [13].

Additionally, in an industrial dc MG, several power electronic converters are connected through a common dc bus, and this dc bus acts as a resonant or tuned circuit with a finite inductance combined with a capacitor. When several dc-dc converters operate in series or parallel in the dc MG, the converters frequencies could coincide with the dc-link bus bar frequency [12]. Consequently, the system could face a catastrophic consequence, such as power oscillation, overshoot, and undershoot in dc bus, even in the worst case, blackouts can happen [10]–[12]. Therefore, to avoid the possibilities of such fatal occurrences, it is essential to a clear understanding of power oscillation in a dc system and develops innovative solutions to minimize its impact.

The extensive analysis and investigation of power oscillation in ac MG are reported in the literature [11], [14]. It is identified that many types of power oscillation can be observed in ac power systems, including intra-plant mode oscillation, local plant mode oscillation, inter-area mode oscillation, and control mode oscillation [13], [15]. On the other hand, in the dc grid, there are mainly two types of oscillation: high-frequency (HF) oscillation and low-frequency (LF) oscillation is observed in contemporary literature [16], [17]. In addition, distributed energy resources like PV and wind have significant impacts on damping performance and generates HF oscillation, as reported in [15], [18], [19]. Typically, power system engineers use stabilizers with synchronous machines to provide damping to obstruct HF and LF oscillation circumstances in the ac system. However, the same singularity would not be appropriate for dealing with these types of oscillations in the case of dc MGs, as the nature of dc system is opposite to the ac system [10], [17]. Therefore, finding the source of the power oscillation and how to maintain the stability of a dc distribution network under such oscillatory conditions requires further exploration.

Recently, significant research has been conducted for finding a suitable methodology to find out various aspects of stability in the dc grid. For instance, Amin *et al.* [20] investigated two methods namely impedance and eigenvalue analysis on the HVDC system and concluded that impedance-based stability analysis is very useful for identifying the local instability at the interfacing point of the converters while the eigenvalue analysis is determined the stability of the whole system regardless installation location of the converters. It is also suggested that in order to identify the source of instability as well as optimum tuning the controller parameters of the converters, it needs to conduct both impedance-based analysis and the eigenvalue-based analysis. Habib *et al.* [9] investigate the voltage oscillation in dc bus on a small scale of dc MG and the impact of various control systems on the dc MG has been studied in [10]; however, the origin of the power oscillation and detailed analytical analysis is an absence in these investigations.

Few studies have been conducted to analyze the small-signal stability on ac/dc MG [20]–[22]. A small-signal model is developed in [20], and the stability analysis is conducted on the hybrid ac/dc MGs. A cross-participation factor (CPF) is presented in [23] and the modal interaction index (MII) approach is introduced to investigate the small-signal stability of an islanded ac MG. Nonetheless, a complete stability investigation, including both the impedance-based method for interfacing point and the state-space modelling and eigenvalue analysis for the entire dc MG for studying HF oscillation is nonappearance in the present literature. This paper fills this gap by investigating the simplified structure of dc MG (as shown in Fig. 1) and the studying the both methods (the impedance-based stability analysis method and eigenvalue-based analysis method) for stability analysis of the dc MG.

A dc microgrid consists of photovoltaic units, energy storage, various types of loads, etc. A conceptual dc microgrid is envisaged and designed for the University of Queensland, Brisbane, Australia. The dc MG includes a rooftop large-scale solar panel, Electric Vehicle (EV) bidirectional dc fast-charging station which equipped with rooftop solar panel, Battery Energy Storage System (BESS), small-scale wind generation and interfaces with the existence or conventional ac grid. Besides, several types of load, i.e., dc load, critical load, ac load, are interfaced with power electronic converters.The main concern of this paper is directed towards the comprehensive small-signal stability (SSS) analysis of the dc bus in the dc microgrid; hence, two units of the converter are designed and investigated for simplicity. Modelling of investigated dc grid having two units of converters is shown in Fig. 2, which is the main building blocks of the proposed dc MG. Two groups of converters, i.e., (boost and buck converter) have been considered for this investigation, as shown in Fig. 2. A dc link-capacitor is used to connect two converters and make a small-scale dc MG.

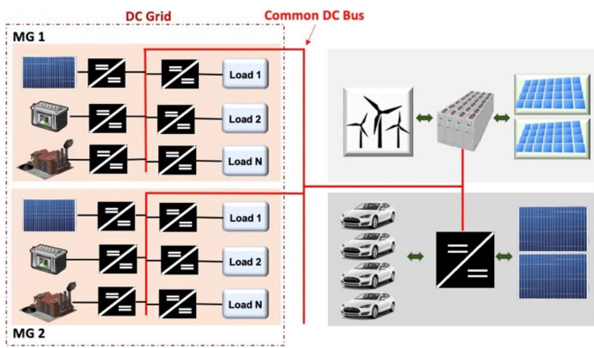

FIGURE 1. Proposed dc MG for the university of queensland.

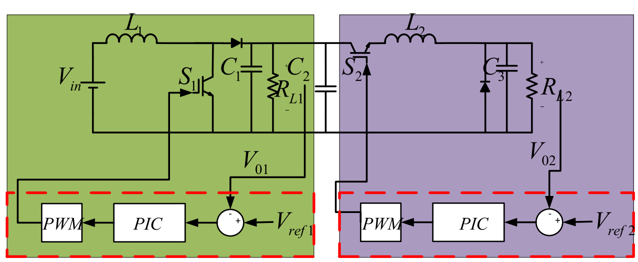

FIGURE 2. Investigated dc microgrid along with the conventional PI controller.

This paper presents a comprehensive small-signal stability analysis on HF oscillation using both the impedance-based stability analysis method and eigenvalue-based analysis method. A detailed state-space model of dc MG is developed, considering the dynamics of power electronic converters. In doing so, first, a comprehensive analytical model of the system is developed for the purpose obtaining the impedance frequency response of the dc-dc converter as well as to identify the critical oscillatory modes of the system. Then a thorough sensitivity analysis has been carried out to study the impact of controller dynamics, circuit parameters, and the load changes. Finally, key results are validated in time-domain simulation. The main contributions of the paper to the state-of-the-art are listed as follows: a) a comprehensive analytical modelling to investigate high-frequency oscillation in dc MG; b) the use of both the impedance-based method and eigenvalue based method to identify the source of instability of the dc MG; c) investigation of critical modes and stability margin of dc MG under worst-case operation conditions by eigenvalue and participation factor analysis; d) identification of the most sensitive mode with respect to disturbances and variation of key parameters.

The rest of the paper is organized in the following. Section II provides a brief synopsis of three methodologies, and Section III presents the modelling of dc MG for small signal stability studies. Section IV discusses the key results along with discussion, and Section V highlights conclusions, contributions and future directions of this research.

II. STABILITY ANALYSIS ON DC MICROGRID

Three methodologies, namely eigenvalue, impedance analysis, and time-domain simulation have been used to conduct small signal stability analysis for many years and each of which has its own merits and demerits [20]. This section will discuss the pros and cons of the methodologies in details.

A. IMPEDANCE ANALYSIS

Middlebrook introduced the theory of impedance analysis in 1976. This theory has been extensively used to analyse SSS for an interconnected system for many years [24]. In addition, this method is useful to check the SSS of PE-based power systems and examines a whole system in accordance with the input and output features of its each and every subsystem [20]. In impedance analysis, system split into two sides first. Then, the output and input impedances have been extracted respectively to form the source and load subsystems. Finally, the ratio of these two impedances is applied to find out the system stability. According to Nyquist theory, the stability of an interconnected system can be determined by the proportion of the output and input impedances $(Z_s/Z_L)\,\frac{Z_s}{Z_L}$. If the curve is far away from (−1,0) point, then its consider as a stable system, and if its cross or touch the point, then it consider an unstable. To restrain the curve circle from (−1,0) point, and to guarantee the SSS, it was recommended that the load impedance Z_L must be higher than the source impedance Z_s under all frequency series, i.e., $|Z_L| \gg |Z_s|$. However, it is inapplicable in many conditions. To guarantee SSS in the interconnected system, Cad M. Wildrick *et al.* first proposed phase margin and gain margin concept in [25]. According to [25], to ensure system stability gain margin (GM) and phase margin (PM) should be at least 6 dB of 60 degrees, respectively. If these criteria maintain while designing a controller; then it is possible to ensure the system stability. However, these benchmarks are appropriate for the open-loop network.

In summary, there are some specific advantages of impedance analysis over the other methods. For example, in impedance analysis, it is easy to find an analytical expression for investigating system stability for a complex, large and multi converter based dc microgrid. Besides, by this methodology, it is possible to detect harmonic oscillation, which is potentially originated from PE devices. Nevertheless, the main drawback of the impedance-based study is that it cannot find out the source of the problem, interaction among controllers and devices, and cross participation factor. Some of the problems can be addressed only by the eigenvalue analysis.

B. EIGENVALUE ANALYSIS

Eigenvalue analysis is well-known for capturing both local and global modes of oscillations. It requires detailed dynamic modelling of each and every component of a system. In eigenvalue analysis, a dynamic power system described by an ordinary differential equation as given in (1)

$$\dot{x} = f\,(x, u, t) \tag{1}$$

where x and u are the vectors of state variables and input variables respectively; and time is denoted by t. The output variables y can be represented as a function of state and input variables, and it can be written as (2)

$$y = g\,(x, u)\,. \tag{2}$$

Then the above nonlinear equations are linearised around an equilibrium point, and the linearized equations can be expressed in general form, as shown in (3) and (4)

$$\dot{x} = Ax + Bu \tag{3}$$

$$y = Cx + Du \tag{4}$$

where: x is a state vector, $x \in R^4$; $x := [i_{l1} v_{c1} i_{l2} v_{c2}]^T$; u is represents the control input vector, $u \in R^2 u = [d_{Boost} d_{Buck}]^T$; y is called the output vector, $y \in R$. A is a $n \times n$ state matrix, and n is the number of states; B is an input matrix has a dimension of $n \times 2$; C is the output matrix, and has a dimension of 1×4. Then, by reducing the system state matrix, SSS can be analysed by looking at the eigenvalue of state matrix A; as given in equation (5)

$$[A - \lambda I]\,\phi = 0 \tag{5}$$

where λ is the eigenvalue, and ϕ is the right eigenvector. The eigenvalues will reflect oscillatory and non-oscillatory modes in the system. Further, a complex eigenvalue can be expressed as given in (6) with the frequency of oscillation using (7), and the damping ration using (8)

$$\lambda = \sigma \pm j\omega \tag{6}$$
$$f = \frac{\omega}{2\pi} \tag{7}$$
$$\xi = -\frac{\sigma}{\sqrt{\sigma^2+\omega^2}}. \tag{8}$$

Depending on the eigenvalues in a positive/negative real part, the system is considered as an asymptotically stable or unstable [17]. For instance, if the eigenvalues are in negative half-plane, the systems are considered as stable. In contrast, if the eigenvalues are in the right half-plane, the system is considered as an unstable. Further, if the system has complex eigenvalues with an imaginary part, it is said to have an oscillatory mode. Furthermore, this analysis also indicates the damping of the modes. For a stable case, the value of ξ always must be greater than zero and higher than a pre-determined value. Nevertheless, usually for an ac system industry standards require. The damping ratio to be 0.05, but for dc system, there is no such standard exist yet [26].

Besides, from the left and right eigenvectors, participation factor analysis can be done, and it can be represented in the following form, $P = [P_1, P_2, P_3, \ldots.., P_n]$; where, $P_1 = \phi_1\psi_1$, $P_2 = \phi_2\psi_2$, $P_3 = \phi_3\psi_3$ and $P_n = \phi_n\psi_n$; where ϕ and ψ are respectively known as the left and right eigenvectors. In eigenvalue analysis, participation factor has been observed to identify the weak modes and to see which element is mainly contributing to making the system unstable.

In eigenvalue analysis, each converter along with their controller is modelled to capture weak modes. The main advantage of eigenvalue analysis is the participation factor analysis using which interaction among devices and sensitivity of modes could be identified. However, in eigenvalue analysis, a linearised model is used, but in the real case scenario, the systems can exhibit nonlinear behaviour. Hence, it is always useful to check the system stability by time-domain analysis.

C. TIME-DOMAIN SIMULATION

Time-domain simulation has been taken into consideration as precisely to study the frequency of oscillations. In the time-domain analysis, the mode is disturbed first. Then the behaviour of state variables has been studied by resolving differential and algebraic equations given in (9) with the help of some numerical integration techniques, i.e., backward Euler and trapezoidal rule.

$$\begin{aligned} \dot{x} &= f(x, u, m, n) \\ 0 &= g(x, y, m, n) \end{aligned} \tag{9}$$

where x and u are the vectors of state variables and input variables respectively; m and n are control and uncontrollable variable.

In a nutshell, it can be said that apart from the experimental study, the time domain simulation is the most accurate way to study the frequency of oscillation. The demerits of this analysis are doing a critical analysis; for instance, various weak modes, the dominant states variable, and the sensitivity of weak modes with respect to the parameter variation cannot be captured from the time-domain simulation. Therefore, impedance scanning, eigenvalue analysis, and time-domain simulation, along with FFT analysis, can be used as complementary solutions to get a complete understanding of high-frequency oscillation.

III. SMALL SIGNAL STATE-SPACE MODELLING OF DC MICROGRID

Following session will demonstrate comprehensive mathematical modelling of proposed dc MG.

A. STATE-SPACE MODEL OF THE BOOST CONVERTER

A simple two-stage boost converter has been considered for this investigation. The boost converter is commonly used to boost up the amplitude of the dc voltage. The average and linearised small-signal state-space model for the boost converter can be expressed as (10)

$$\begin{bmatrix} \frac{dil_1}{dt} \\ \frac{dv_{01}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-D)}{L_1} \\ \frac{(1-D)}{C_1} & -\frac{1}{R_1C_1} \end{bmatrix} \begin{bmatrix} il_1 \\ v_0 \end{bmatrix} 1 + \begin{bmatrix} \frac{1}{L_1} \\ 0 \end{bmatrix} v_{in} \tag{10}$$

where C_1, L_1, R_1 respectively are the capacitor, inductor, and resistor in the boost converter. Besides, i_{l1} is the inductor current in a boost converter, v_{01} and v_{in} are the respectively capacitor voltage and input voltage in a boost converter, and D is the duty cycle of the boost converter.

B. STATE-SPACE MODEL OF PI CONTROLLER

A controller is usually used to get regulated and fixed results. To get a stable and controlled output voltage, the PI controller is considered in this investigation. State-space model of PI controller can be written as (11)

$$\begin{aligned} \frac{d\beta}{dt} &= \left[V_{dcref} - V_{out}\right][\beta] \\ d &= K_p\left(V_{dcref} - V_{out}\right) + K_i\beta \end{aligned} \tag{11}$$

where K_p is the proportional gain and K_i is the integral gain of the investigated PI controller, and β is introduced to represent the state vector of the integrator.

C. STATE-SPACE MODEL OF THE INVESTIGATED BUCK CONVERTER

A simple two-stage buck converter has been considered in this investigation. Buck converter is used to reduce the magnitude of the dc voltage in dc bus. The small-signal state-space model for the buck converter along with a PI controller can be expressed as (12)

$$\begin{bmatrix} \frac{dil_2}{dt} \\ \frac{dv_{02}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_2} \\ \frac{1}{C_3} & -\frac{1}{R_3C_3} \end{bmatrix} \begin{bmatrix} il_2 \\ v_{02} \end{bmatrix} + \begin{bmatrix} \frac{D}{L_2} \\ 0 \end{bmatrix} v_{in} \tag{12}$$

where, C_3, L_2, R_2 respectively are the capacitor, inductor, and resistor in the buck converter. In addition, i_{l2} is the inductor current in a buck converter, v_{02} and v_{in} are the respectively capacitor voltage and input voltage in a buck converter, and D is the duty cycle of the buck converter.

D. STATE-SPACE MODEL OF THE BUCK CONVERTER WITH PI CONTROLLER

To get fixed and regulated output voltage in the buck converter side, the PI controller has been considered in this investigation. The small-signal state-space model for the buck converter along with a PI controller can be expressed as (13)

$$\begin{bmatrix} \frac{dil}{dt} \\ \frac{dv_0}{dt} \\ \frac{d\beta}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{L_2}\left(-1 - V_{in}K_p\right) & \frac{K_i V_{in}}{L_2} \\ \frac{1}{C_3} & -\frac{1}{R_2 C_3} & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} il \\ v_0 \\ \beta \end{bmatrix} \tag{13}$$

E. STATE-SPACE MODEL OF INVESTIGATED BOOST CONVERTER WITH PI CONTROLLER

The small-signal state-space model for the boost converter along with a PI controller can be expressed as (14), as shown at the bottom of the page.

F. STATE-SPACE MODEL OF COMPLETE DC GRID

A detailed small-signal state-space model is necessary to do eigenvalue, participation factor and sensitivity analysis. To do eigenvalue analysis in dc microgrid, need to find the overall system state matrix. The complete investigated small-signal state-space model can be expressed as (15), as shown at the bottom of the page, and it is obtained by using the individual subsystem (13), and (14).

G. ANALYTICAL EXPRESSION FOR IMPEDANCE SCANNING OF THE INVESTIGATED BOOST CONVERTER

The output (o/p) and input (i/p) impedance of the boost converter can be expressed as the ratio of the o/p and i/p

$$\begin{bmatrix} \frac{dil}{dt} \\ \frac{dv_0}{dt} \\ \frac{d\beta}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{L_1}\left(-1 + K_p V_{ref} - 2V_0 K_p + K_i\beta\right) & \frac{K_i V_0}{L_1} \\ \left(\frac{1}{C_1 + C_2}\right)\left(1 - K_p V_{ref} + K_p V_0 - K_i \beta\right) & \left(\frac{1}{C_1 + C_2}\right)\left(K_p I_l - \frac{1}{R_1}\right) & \left(\frac{K_i I_l}{C_1 + C_2}\right) \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} il \\ v_0 \\ \beta \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} \frac{dil_1}{dt} \\ \frac{dv_{01}}{dt} \\ \frac{d\beta_1}{dt} \\ \frac{dil_2}{dt} \\ \frac{dv_{02}}{dt} \\ \frac{d\beta_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{L1}\left(-1+K_{p1}V_{ref1}-2V_{01}K_{p1}+K_i\beta_1\right) & \frac{K_{i1}V_{01}}{L_1} & 0 & 0 & 0 \\ \left(\frac{1}{C_1+C_2}\right)\left(1-K_{p1}V_{ref1}+K_{p1}V_{01}-K_{i1}\beta_1\right) & \left(\frac{1}{C_1+C_2}\right)\left(K_{p1}I_l-\frac{1}{R_1}\right) & \left(\frac{K_{i1}I_{l1}}{C_1+C_2}\right) & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{L_2}\left(-1-V_{o1}K_{p2}\right) & \frac{K_{i2}V_{o1}}{L_2} \\ 0 & 0 & 0 & \frac{1}{C_3} & -\frac{1}{R_2C_3} & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix} \times \begin{bmatrix} il_1 \\ v_{01} \\ \beta_1 \\ il_2 \\ v_{02} \\ \beta_2 \end{bmatrix} \tag{15}$$

voltage and current respectively; as given in (16) & (17).

$$Z_i(s) = sL_1 + \frac{(1-D)^2 \times R_1 \times \frac{1}{sC_1}}{R_1 + \frac{1}{sC_1}} \tag{16}$$

$$Z_0(s) = \frac{s^2 + s\left(C_1 \times R_1\left(1+D^2\right) + L_1 + \left(R_1 \times D^2\right)\right)}{L_1 \times C_1 \times R_1} \tag{17}$$

Likewise, the closed-loop output impedance of the boost converter is

$$Z_{ocl}(s) = \frac{Z_o(s)}{1+T(s)} \tag{18}$$

Here, loop gain $T(s)$ can be found by multiplying the transfer function of the controller, converter and pulse with the modulator. $T(s) = G_c(s)\, G_p(s)\, G_m(s)$; considering unit feedback. where, $G_c(s)$ is the transfer function of the controller; $G_p(s)$ is the transfer function of pulse width modulator, and G_m is the transfer function of pulse width modulator. Loop gain $T(s)$ can be expressed as (19):

$$T(s) = \left(K_p + \frac{K_i}{s}\right) \times \frac{\left(\frac{V_{in}}{(1-D)^2}\right) \times \left(1 - s\frac{L_1}{(1-D)^2 \times R_1}\right)}{\left(\frac{L_1 \times C_1}{(1-D)^2}\right)\left(s^2 + s\left(\frac{1}{C_1 \times R_1} + \frac{(1-D)^2}{L_1}\right)\right) + \frac{(1-D)^2}{L_1 \times C_1}} \tag{19}$$

H. ANALYTICAL EXPRESSION FOR IMPEDANCE SCANNING OF THE INVESTIGATED BUCK CONVERTER

The input and output impedances of the open-loop buck converter can be expressed as (20) and (21).

$$Z_i(s) = \frac{\left(s^2 L_2 C_2\right) + R_2}{D^2 \times (1 + sR_2C_2)} \tag{20}$$

$$Z_0(s) = \frac{sL_2R_2}{sL_2 + s^2 + R_2C_2L_2 + R_2} \tag{21}$$

Consequently, the input and output impedances of the closed-loop buck converter can be written as in (22) & (23).

$$Zicl(s) = \frac{Z_i(s) \times R_2 \times (1 + T(s))}{R_2 + Z_i(s) - D^2 \times T(s)} \tag{22}$$

$$Z_{ocl}(s) = \frac{Z_o(s)}{1+T(s)} \tag{23}$$

Here, loop gain $T(s) = G_c(s)\, G_p(s)\, G_m$; Considering unit feedback. $T(s)$ is the loop gain of the buck converter, and it can be written as (24)

$$T(s) = \left(K_p + \frac{K_i}{s}\right) \times \left[\left(\frac{V_{in}}{L_2 \times C_2}\right) \times \frac{(1 + s \times C_2)}{s^2 + s\left(\frac{1}{C_2 \times R_2} + \frac{1}{L_2}\right) + \frac{1}{L_2 \times C_2}}\right] \tag{24}$$

As a result, the corresponding total impedance which can be seen from the dc-link can be drawn in the Matlab Simulink platform, which is presented in the following session.

TABLE 1. Parameters of the dc-dc converters.

Boost Converter		Buck Converter	
$V_s = 20V$	$L_1 = 157e-6H$	$V_s = 40V$	$L2 = 1.5e-3H$
$V_o = 40V$	$R1 = 95\Omega$	$V_o = 20V$	$R2 = 75\Omega$
$D1 = 0.5$	$C1 = 470e-6F$	$D2 = 0.5$	$C2 = 470e-6F$
$Kp_1 = 0.001$	$Ki_1 = 0.05$	$K_{p_2} = 0.9$	$Ki_2 = 0.5$

IV. STABILITY ANALYSIS

This section focuses on the sensitivity of system parameters on the stability of the overall dc grid system by changing load, inductance, dc-link capacitance, and controller gains in MATLAB Simulink platform.

A. IMPEDANCE ANALYSIS

This subsection presents the impedance-based approach to investigate dc MG stability. Two groups of converters have been considered for this study. The boost converter has been considered in the source side, whereas buck converter has been placed in load side. To construct a prototype of the dc microgrid, the converters are first designed individually in a Matlab Simulink platform. Then a proportional and integral controller is selected on the basis of a root locus, phase margin (PM), step response, and gain margin (GM). The values of proportional (P) and integral (I) gains respectively (i.e., K_p = 0.0011262 and K_i = 0.05) are selected, based on PM = 95 degrees and GM = 15dB for the source-side converter. Following the same procedure, a conventional PI controller is chosen for the load-side buck converter. An optimal proportional and integral gain (i.e., K_p = 0.965 and K_i = 0.5) are considered, along with PM and GM, 90 degrees and 15dB respectively. Lastly, a small scale dc microgrid is formed by combining these converters along with their controllers. The parameters of the investigated converters are given in TABLE 1.

Then, an impedance analysis has been conducted in the MATLAB Simulink platform, which is presented in Fig. 3. From Fig. 3, it can be seen that output impedance is far away from the input impedance except for two resonance peak, which is 293 Hz and 0.275 Hz.

Overall, in impedance analysis, four sensitive modes have been identified, and they are 0.275 Hz, 190 Hz, 293 Hz, and 1140 Hz. However, the source of the problem and the critical mode that could contribute to oscillation could not be identified. For this, the eigenvalue analysis is recommended. To find out the sensitivity of the modes an eigenvalue analysis has been conducted in the following sub section.

B. EIGENVALUE ANALYSIS

This section presents the eigenvalue-based approach to identify critical modes and the associated modal characteristics in the dc grid. To find out the source of the problem, interaction among controllers and devices, and cross participation factor, a thorough investigation of eigenvalue analysis has been conducted.

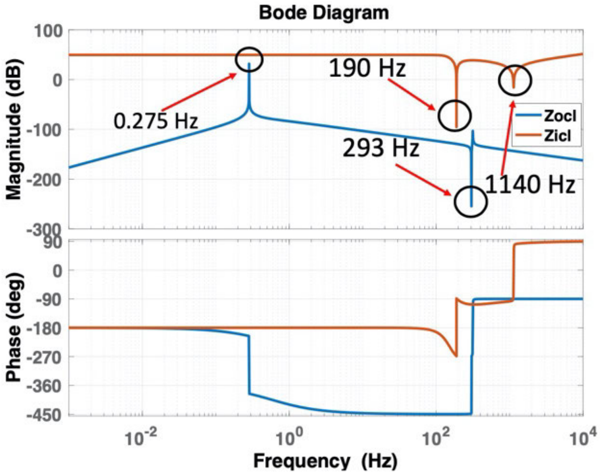

FIGURE 3. Impedance scanning on dc bus. O/P impedance from the source side and I/P impedance from the load side.

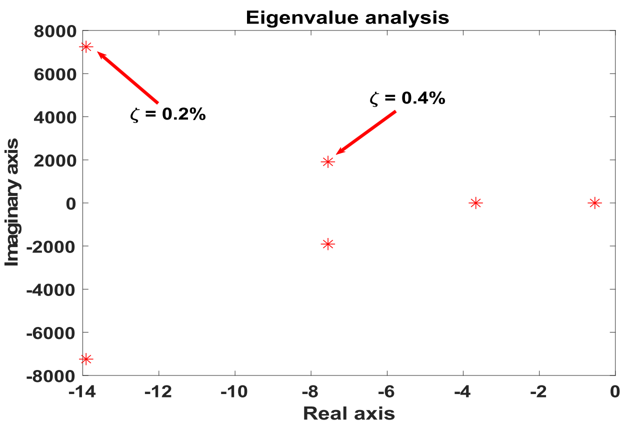

FIGURE 4. Stable operation of dc MG.

It is found that an HF oscillation, having meagre damping ratio (0.004) for 293.78 Hz and 0.0019 for 1153.6 Hz, as demonstrated in Fig. 3. It is noticed that risk of instability from eigenvalues of λ_2 is greater than that from λ_1; as λ_2 has lower damping ratio compare to λ_1. Hence, it is assumed that, with the variation of a system parameter, this critical mode might move to the right half-plane and make system oscillatory and unstable. Subsequently, a participation factor analysis has been conducted to see the modes/states contributes mostly to the system, as presented in Table 2.

TABLE 2. Eigen value for complet system.

$\lambda_{critical}$	$\xi(\%)$	$f(Hz)$	Dominant states	Remarks
-7.5554 ± 1844.9i	0.4	293.78	i_{l1}, v_{o1}	Boost Converter
-13.914 ± 7244.5i	0.2	1153.6	i_{l2}, v_{02}	Buck Converter

From participation analysis, it is found that the 293 Hz mode is contributed by the boost converter, and 1154 Hz mode is contributed by the buck converter. Consequently, to see the system sensitivity against small changes, the parameter a details sensitivity analysis has been conducted in the following subsection.

1) CASE STUDY 1 (VARIATION OF CONTROLLER PARAMETER IN BOOST CONVERTER)

In this case study, the small variation of the controller parameter is applied in source side boost converter, and the trajectories of sensitive modes are presented in Fig. 5, and Fig. 6, respectively. Fig. 5 illustrates the root-locus of the investigated modes under the variation of proportional gain of the boost converter.

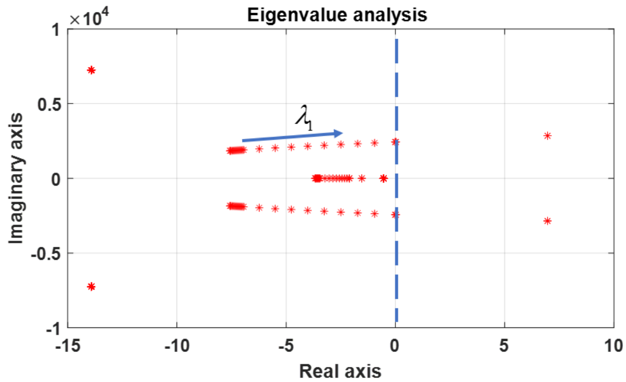

FIGURE 5. Impact of variation in controller parameter (only Kp in boost converter) on dc microgrid.

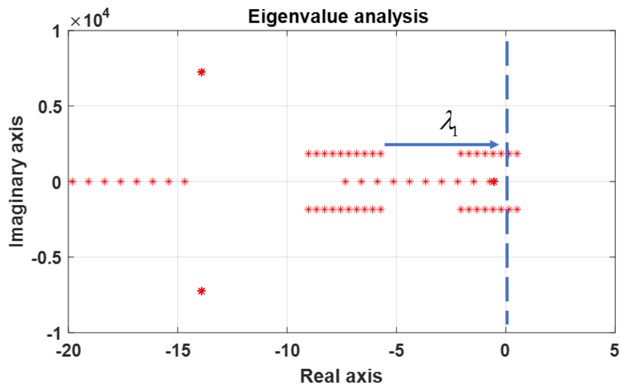

FIGURE 6. Effect of change in controller parameter (only Ki in boost converter) on dc microgrid.

As the parameter of the gain decreasing, modes of λ_1, moved to the right half-plane, which indicates degradation of the dynamic response of system stability. Trajectories of sensitive modes under variation of the integral controller is presented in Fig. 6. A similar scenario has been observed that with respect to decreasing integral gain value, λ_1 shift to the right half-plane.

As can be observed, with the changing of the PI controller parameter, the overall system becomes very sensitive, and the system becomes unstable as the eigenvalues move to the right-half plane. Further, keeping a stable condition of dc microgrid, boost converter proportional and integral parameter should be tuned between (0.0011 to 0.011) & (0.05 to 0.24) respectively. It is also noticed that with the increasing of PI, system small-signal stability deteriorate drastically.

2) CASE STUDY 2 (VARIATION OF CONTROLLER PARAMETER IN BUCK CONVERTER)

This case study investigates the sensitivity of the buck converter gains on the stability of the overall dc microgrid system. A small variation of PI gain in a particular range has been considered in this case study. Fig. 7 presents root loci due to the variation of proportional gain. As the proportional gain of the boost converter controller varied, λ_2 notoriously moved toward to right half-plane; whereas λ_1 keep fixed in his position.

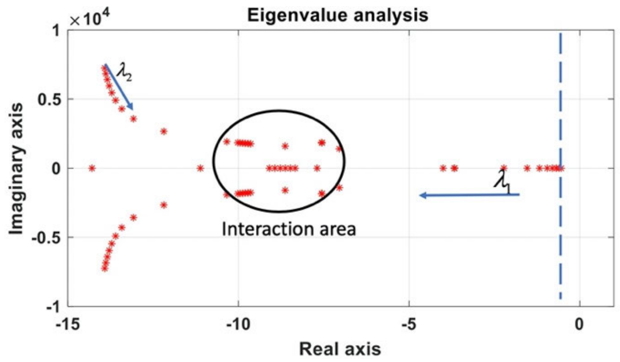

FIGURE 7. Impact of variation in controller parameter (only Kp in Buck converter) on dc microgrid.

Further, It is noticed that the controller dynamics can significantly influence the eigenvalues movements. With the variation of gain parameter, λ_2 approached to λ_1, and two eigenvalues came closer to each other and interacted when boost and buck converter tuned at 0.0011 and 0.035 respectively. Frequency of oscillation (293 Hz) has been observed during the interaction point, as marked by a circle. It indicates the resonance phenomenon, which can potentially deteriorate the system stability.

An opposite trend is observed in Fig. 8. Under the variation of integral gain of boost converter, the eigenvalues have been found in the stable region. As can be seen that the overall system is not that much sensitive as it was seen in the case of the boost converter.

3) CASE STUDY 3 (VARIATION OF -LINK CAPACITANCE)

Fig. 9, presents the stability of the system with respect to changes dc-link capacitance. As can be seen, by increasing the dc-link capacitance, the eigenvalue with 293 Hz mode slowly travels adjacent to the imaginary axis, and after 2100μ F, the eigenvalue of the system moves to the right-hand side, and the system becomes unstable.

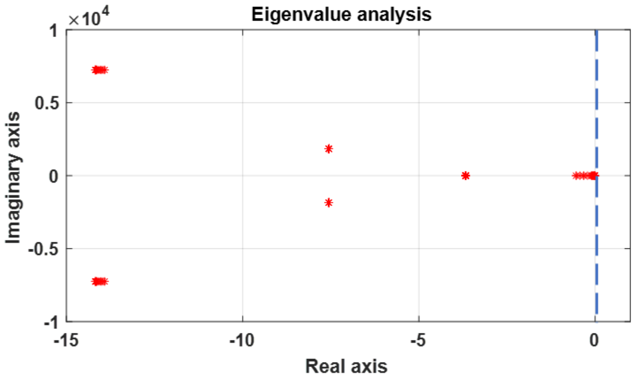

FIGURE 8. Impact of variation in controller parameter (only Ki in Buck converter) on dc microgrid.

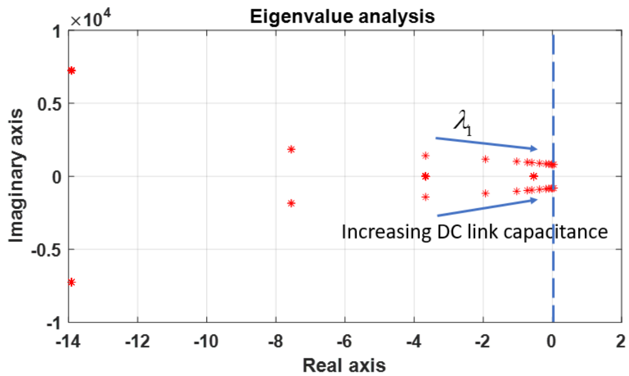

FIGURE 9. Impact of variation of dc-link capacitance on the dc microgrid.

4) CASE STUDY 4 (VARIATION OF LOAD POWER)

The fourth case study presents the stability of the overall system with respect to load changes.

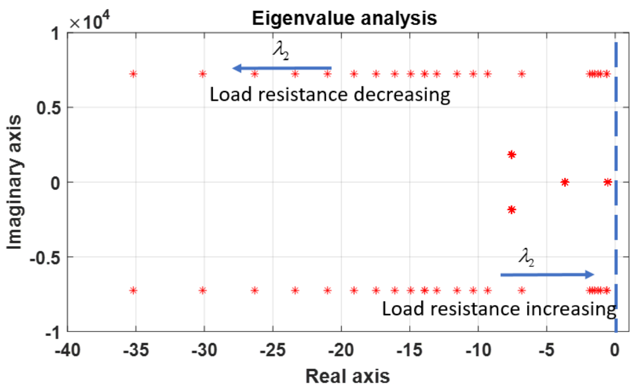

FIGURE 10. Variation of resistive load in buck converter on dc grid.

From Fig. 10, it is observed that by decreasing load resistance, the eigenvalues gradually moves to the left half-plane. On the other hand, by the increasing load, the eigenvalues slowly move adjacent to the imaginary axis, but still fits the left half complex plane, and the system remains stable.

5) CASE STUDY 5 (VARIATION OF INDUCTANCE)

The fifth case study is dedicated to investigating the sensitivity of the systems with changes both

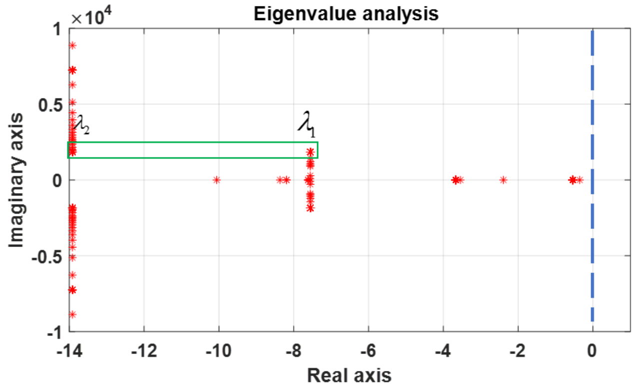

FIGURE 11. Impact of inductance on the dc grid.

converters inductance. An interesting scenario has been observed in this case study, as presented in Fig. 11. Increasing the value of buck converter inductance significantly influenced the eigenvalues movements. It is noticed that imaginary part of λ_1 and λ_2 becomes equal when boost and buck converter tuned at 157e-6 H and 21.3e-3 H respectively. Frequency of oscillation (293 Hz) has been observed during the interaction point, as marked by square. Hence, the interaction between these modes potentially occurs. The interaction event might lead to more system in an unstable situation. It also indicates the resonance condition, which can possibly deteriorate the system stability.

Overall, in eigenvalue analysis, two sensitive modes of high frequency have been identified. One is 293 Hz, and the other is 1153.6 Hz. It has been noticed that both eigenvalue and impedance analysis pick up 293 Hz frequency of oscillation. However, in impedance analysis, high frequency like 1153 Hz instead of 1140 Hz, and in eigenvalue, low frequency of 0.295 Hz were not picked up. Some of the key results are validated in time-domain simulation in the following section.

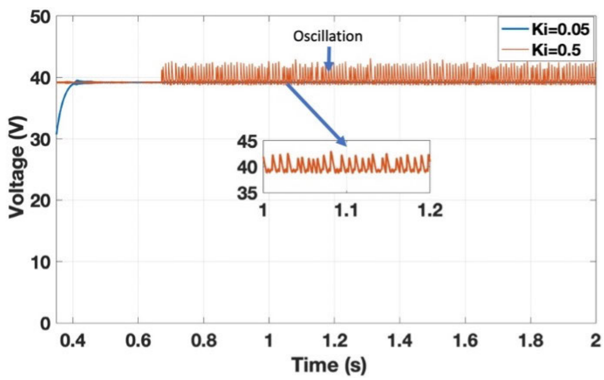

FIGURE 12. The stable dc bus voltage influenced by integral controller dynamics.

V. TIME DOMAIN SIMULATION RESULTS

The effect of controller dynamics on dc bus within dc microgrid is visualized using time-domain simulation, as depicted in Fig. 12. This result corroborated the previous sensitivity analysis obtained with the help of eigenvalue analysis as shown in Fig. 5. Two scenarios are demonstrated here, and when the integral controller gain of the boost converter is tuned at 0.05, the more damped oscillation at dc bus voltage has been observed.

In this gain setting, two sensitive modes and their oscillation frequencies were far away from the imaginary axis. Hence, an oscillation free, stable dc bus voltage is observed. As the integral control gain is tuned at 0.5, a continuous voltage oscillation has been found at dc bus. At this particular gain setting, one mode goes to the right half-plane; therefore, significant deterioration of the dc bus voltage is observed. From Fig. 12, it is also noticed that the dc bus voltage at the microgrid is very sensitive and becomes unstable due to the small variation of the controller parameter. Further, to find out the modes of the frequency of oscillation, an FFT analysis are conducted, as shown in Fig. 13. A modest growth with a resonance peak is noticed around 293 Hz, which is similar to the impedance scanning. However, it falls gradually and remains to keep approximately steady. In general, the amplitude is in a decent array apart from for resonance frequency, which is one of the critical focal points of this investigation.

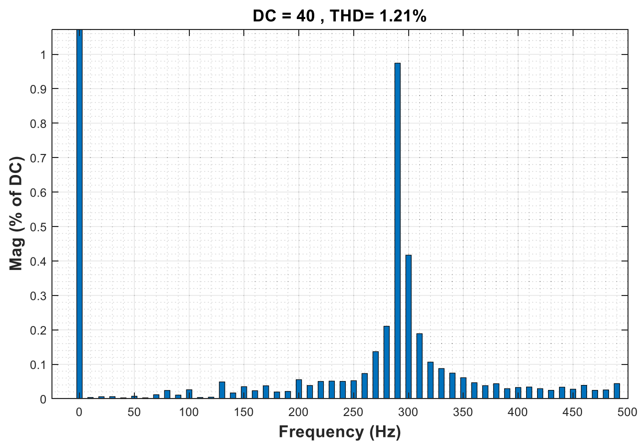

FIGURE 13. FFT analysis on the dc bus.

The influence of controller dynamics (proportional controller) in the source side converter on the dc bus is envisaged in time-domain simulation and presented in Fig. 14 and Fig. 15.

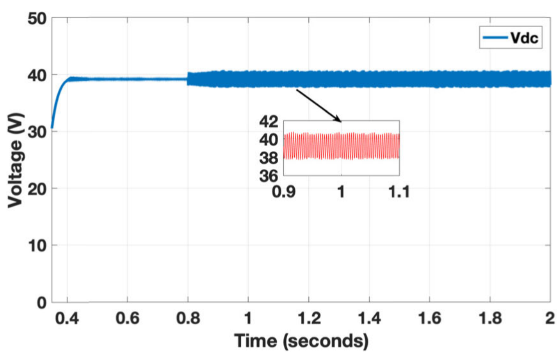

FIGURE 14. The stable DC bus voltage influenced by the proportional controller dynamics.

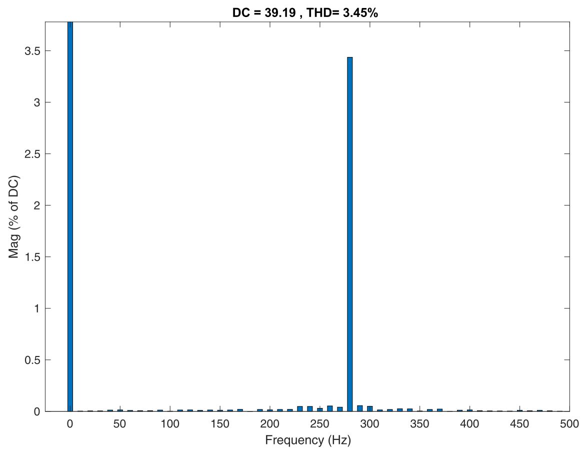

FIGURE 15. FFT analysis on the dc bus.

Here, a disturbance has been applied in the source side, and proportional gain of the boost converter is tuned at 0.11. As the proportional control gain is modified at 0.11, a continuous voltage oscillation has been found at the dc bus. At this particular gain setting, one mode goes to the right half-plane; therefore, significant deterioration of the dc bus voltage is observed, as predicted in the sensitivity analysis in Fig. 4. Further, to find out the modes of the frequency of oscillation, an FFT analysis are conducted, as shown in Fig. 15. A modest growth with a resonance peak is noticed around 290 Hz, which is similar to the participation factor analysis and impedance scanning.

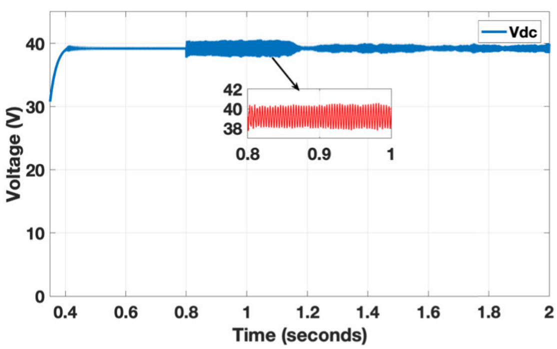

FIGURE 16. The stable dc bus voltage influenced by the load side controller dynamics.

The consequence of controller dynamics in the load side converter (buck converter) has been depicted in Fig. 16.

A chaos types of voltage oscillation at the dc bus is observed due to the changes of the controller parameter in a buck converter.

At this particular gain setting (boost and buck converter tuned at 0.0011 and 0.035 respectively), two modes come close to each other, and interaction happen; therefore, significant deterioration of the dc bus voltage is observed. Further, to find out the modes of the frequency of oscillation, an FFT analysis are conducted, as shown in Fig. 17. A modest growth with a resonance peak is noticed around 293 Hz, which is similar to the impedance scanning. Fig. 18 demonstrate

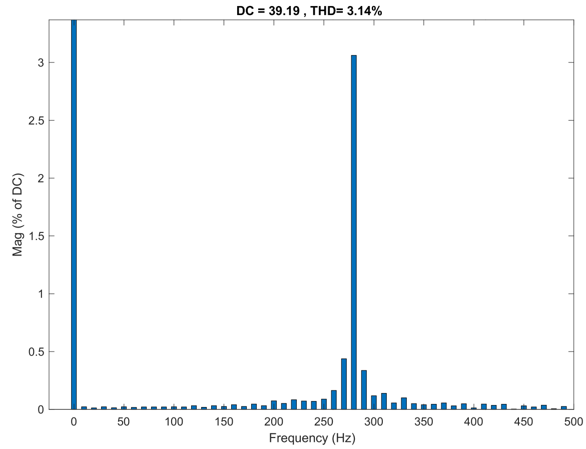

FIGURE 17. FFT analysis on the dc bus.

the dynamic response of dc bus voltage in consequence of the variation of dc-link capacitance. To excite the sensitive modes, small perturbations is applied between 0.6-0.7 sec; and overshoot and undershoot on the dc bus during the disturbance time is observed.

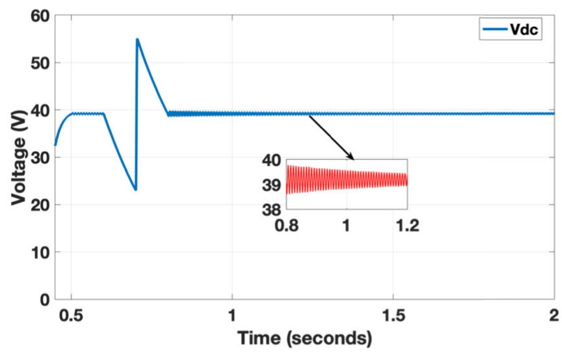

FIGURE 18. Impact of inappropriate DC-link capacitance FFT analysis on the DC bus.

It is noticed that the overshoot and undershoot have disappeared when the disturbance is removed. However, a continuous power oscillation at dc bus is overserved even though the disturbance has been removed. It is assumed that this oscillation is due to the impact of the inappropriate dc-link capacitance.

VI. CONCLUSION

Minimizing global warming and promoting a sustainable and greener environment is one of the key priorities in today's world. With these priorities, a dc grid can contribute enormously to meeting these priorities; covering all three pillars of sustainability concepts which are the social, economical and environmental aspects. It has a better integration facility with RERs such as PV, wind, BES, supercapacitors, and EV fast-charging stations. However, integrating RERs along with other modern technologies into a dc microgrid could introduce instability problems. This research paper has focused on stability, particularly oscillatory stability leading to interactions and resonance in a dc MG.

To do so, a complete analytical model of dc MG to analyze the small-signal stability performance is presented first. Then the detailed sensitivity analysis is presented in a systematic way, and different sensitive modes are identified. It is found that controller dynamics can significantly contribute voltage oscillation in dc bus. In the worst case, it can destabilize the dc bus voltage. The results also show that there are weak high-frequency oscillation modes in dc MG. It is further noticed that the fluctuation of the boost converter controller parameter causes very fast degradation of dc-link voltage and can make the system unstable. It is found that non-linear behaviour of sensitive modes in dc MG could potentially cause the modal interaction; which might cause resonance phenomenon and lead to system instability. It is also noticed that dc link capacitance is the key contributor to resonance on the DC bus, and has a significant impact on total system stability.

Finally, the analytical findings are validated here through time domain simulation. The bounds of the controller parameters are given in the paper as well. Considering the uncertain operating condition of dc microgrid, advanced control may be used in future. The effect of the advanced control on the DCMG will also be assessed and reported in future

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