Damping Oscillation and Removing Resonance in a RE Based DC Microgrids

Mohammad Habibullah\textsuperscript{1}, Member, IEEE, Krischonme Bhumkittipich\textsuperscript{2}, Senior Member, IEEE, Nadarajah Mithulananthan\textsuperscript{3}, Senior Member, IEEE, Rahul Sharma\textsuperscript{4}, Senior Member, IEEE, and Firuz Zare\textsuperscript{5}, Fellow, IEEE

\textsuperscript{1,3,4}School of Information Technology and Electrical Engineering, The University of Queensland, Australia
\textsuperscript{2}Department of Electrical Engineering, Rajamangala University of Technology Thanyaburi, Pathum Thani, Thailand

Corresponding author: K. Bhumkittipich (e-mail: krischonme.b@en.rmutt.ac.th).

ABSTRACT Disturbances, including uncertainties are a common phenomenon in power grids, and they can occur in source or load side at different time or simultaneously in both sides. Among the most frequent disturbances, source and load uncertainties are considered as the most catastrophic features. These disturbances can deteriorate the performances of the associate controller and contribute to oscillation and resonance. Conventional Proportional Integral (PI) controllers fail to provide supply quality assurance and system security against moderate to strong disturbances. If a disturbance occurs, it usually deteriorates both controller performance and supply voltage quality at DC bus in microgrids. This issue, however, has not been fully understood and addressed in the existing literature. Hence, this paper presents the effect of the conventional PI controller in a DC microgrid under disturbances. Consequently, a few case studies has been conducted with traditional single-variable controllers in a real time simulation environment and found that disturbances can causes overshoot or undershoot, along with power oscillation at DC bus. Thus, to overcome this oscillation and to enhance the stability and resilience of the DC microgrid, a Linear Quadratic Regulator (LQR) controller is proposed. Results demonstrate that the LQR controller can handle small to moderate disturbances and stabilise the voltages at the DC bus when compared to a conventional PI controllers. It can also minimize overshoot and undershoot along with damping power oscillation at common DC bus and removing the possibilities of resonance.

INDEX TERMS- DC Microgrid, disturbances, power oscillation, resonance, LQR controller.

I. INTRODUCTION
DC grids, including microgrids are emerging as a future electricity delivery system due to increase use of Renewable Energy Sources (RES) and dynamic loads based on power electronics (PE) technology. There are a number of advantages of DC microgrid over the AC counterpart such as the absence of reactive power, skin effect, angular and frequency instability problems[1-5]. On the other hand, in terms of economic prospects, DC microgrid is highly efficient, cost-effective, and reliable, compared to the AC microgrid [6-10]. Nevertheless, there are some key technical challenges that need to be resolved for making it practical from the research stage. Among the technical challenges power oscillation and resonance at DC bus are very complicated in DC microgrids.

A DC microgrid is a combination of multiple sources (i.e., PV, batteries, fuel cells and capacitors) and loads, which are interconnected through dc - dc converters. These converters are often regulated by associated controllers to assist them in giving smooth power to achieve a desired system response. However, the performance of these controllers deteriorates due to variations or disturbances in converters associated with the dynamic characteristics of the system. Nevertheless, the impact of various disturbances in the DC grid has been ignored while designing controllers in [11, 12].

Among the disturbances, source and load uncertainties are considered the most catastrophic features, deteriorate controller performance and contributes to power oscillation leading to resonance at common DC bus. The literature has reported different control designs (e.g., optimal, finite-time, model predictive, robust, backstepping and coordinated control methods) for improving the performance of dc grids or their equipment in various aspects [13, 14].

In the current literature, while designing controllers for dc microgrids, the impact of small to large disturbances on a dc
bus has been overlooked. However, at this dc bus, maintaining stable voltage without any oscillation or resonance is very crucial. If the stability of any dc bus deteriorates due to disturbances or existence of resonance conditions, then the system might be unstable, and in the worst case, a system collapse is possible. An initial investigation shows power oscillation at a dc bus, while two units of converters-associated controller are connected together due to various disturbances. It is also found that a single variable controller cannot handle disturbances, causing a significant power oscillation as the operating point changes as a result of disturbances. Hence, it is a requirement to design a multivariable controller to suppress oscillation and remove resonance at the common dc bus. The key contributions of this paper are as follows:

1. **A study of conventional single variable interconnected devices at DC bus:** This paper shows that the PI controller can be designed well and it can work for single-input single-output (SISO) systems. However, for multivariable systems, PI is insufficient, and stability margin cannot be guaranteed. Therefore, robustness to significant disturbances can result in instability and poor performance implications. An alternative to PI is to use a multivariable control approach. This paper develops a Linear Quadratic Regulator (LQR) controller, which is based on the duty cycle of associated converters for improving dc bus voltage quality and is subject to strong disturbances. The fundamental difference between the conventional design and the proposed method is that instead of inductor currents and dc output voltages, the duty cycle is considered as an input. The concept behind this consideration is that while a disturbance occurs, it degrades the performance of the controller. As a result, the operating point changes and the duty cycle behaves as abnormal. Hence, if the duty cycle can be controlled during the disturbance, it is then possible to control dc bus voltage quality against disturbances.

   It is further showed that even a well-designed classical feedback controller, which works well individually in isolation with adequate stability margins, may result in instability and sustained oscillations upon interconnection with a dc microgrid. This would happen due to the interaction of different dynamics in the system. The conditions get even worse when a disturbance occurs at the source or load side or concurrently on both sides. Such situations may result in resonance at a dc bus and degrade the equipment’s life. Resonance conditions may also lead to a voltage collapse situation in the dc grid.

2. **Design of a multivariable controller:** To guarantee global stability and remove power oscillation at a dc bus, a multivariable controller is designed. Initially, a mathematical model of the dc grid is presented. The objective function of the LQR controller is then formulated. Finally, the optimal gain is extracted to control the dc bus. In addition, the controller performance is successfully validated through two case studies. Results show that the proposed controller can suppress the overshoot and minimise the power oscillation at a dc bus for small to moderate disturbances. Hence, the stability of the dc bus can be improved.

   The rest of the paper is organised as follows: Section II provides a brief explanation about power oscillation and resonance in the dc grid, and Section III presents a brief synopsis of the configurations of dc microgrid. Section IV elaborates the design procedure of advanced LQR controller and relevant mathematical models in detail. Section V discusses the key findings, and Section VI highlights the conclusions, major contributions and future directions of this research.

### II. POWER OSCILLATION AND RESONANCE

Power oscillation is a critical issue in the dc grid. It is originated from various factors such as interaction among controllers, poorly designed controllers, line switching, line faults and a rapid change of generators’ outputs. There are many types of power oscillation in AC power systems such as intrapanel mode oscillation, local plant mode oscillation, inter-area mode oscillation, control mode oscillation. In the dc grid, two forms of oscillation [i.e., high-frequency (HF) and low-frequency (LF)] are noticed in [15, 16]. Renewable resources, namely solar and wind farms also have a substantial influence on damping performance [17-20]. In addition, poorly designed controllers can create a noxious or adverse effect on oscillation in dc grids. Besides, PE devices and Distributed Energy Resources (DERs) can cause HF oscillation in dc microgrid [16]. To mitigate the HF oscillation, a damping approach is proposed in [16]. Nevertheless, the influence of LF oscillation in dc grids was not considered in this paper. The high current oscillation occurs due to a high voltage step-up in dc grids. To address the above-mentioned problem, a multilevel MVDC link strategy (MMS) was proposed to minimise the current oscillation and improve the efficiency of dc grids [21]. An eigenvalue-based stability analysis is presented in [14], and it is found that the primary source of LF oscillation is active power controller. The impact of various types of loads in dc microgrids is investigated in [22]. The authors observed that the current oscillatory problem, which are potentially generated from unbalance AC loads. Considering the aforementioned problems, the authors proposed an effective control strategy which could be applied to a multi-bus dc microgrid.

   Capacitor banks are usually used as an economical solution for power factor corrections in distribution networks, but the negative aspect of capacitor banks and filters are as potential resonance. Ref. [6] presented resonance that can be generated from either capacitors or impedance or from both in dc grids. If the driving system frequency coincides with driven subsystem frequency, then the system could face catastrophic consequences and a high possibility to result in a system collapse. In addition, PE converters have electromagnetic interference (EMI) filters, which cause inrush currents and might lead to voltage oscillations at dc bus.
Resonance is a primary reason for dc current harmonics in case of dc microgrids, and it happens in a certain resonant frequency [14]. Additionally, while driving frequency is adjacent to the natural frequency of the network, the system starts to fluctuate, and when it matches, at that time it fluctuates sternly. Nonetheless, it is challenging to minimise the power oscillation while the resonance exists in a system. As is previously discussed, the configuration of a dc grid and its characteristics is different from that of an AC system; hence, these issues need to be thoroughly investigated.

III. SYSTEM CONFIGURATION

A dc grid consists of different components such as photovoltaic units, energy storage systems and various types of loads. A conceptual dc microgrid is envisaged and designed for the University of Queensland, Brisbane, Australia, as shown in Fig.1. The dc microgrid includes a rooftop large-scale solar panel that is associated with an EV bidirectional dc fast charging station, a Battery Energy Storage System (BESS) and a small-scale wind generator.

The dc microgrid interfaces with an existing or conventional AC grid. In addition, several types of loads (i.e., AC, dc, and critical loads) are interfaced with power electronic converters in the microgrid.

![DC Grid Diagram](image)

FIGURE 1. A dc microgrid proposed for the University of Queensland.

As shown in Fig. 1, the BESS is connected at common dc bus through dc-dc converters, whereas the conventional AC grid is connected with two stages of converters. A large-scale dc fast charging EV-BESS station is also connected through a smart dc-dc bidirectional converter powered by the rooftop solar PV panel. The system is a 10 MW testbed case study and the system capacity can be increased with a higher load demand. In this paper, the main concern is directed towards the stability of the dc bus. Consequently, two units of the converter are designed and investigated for simplicity.

![Block Diagram](image)

FIGURE 2. Block diagram of the investigated simple dc microgrid.

The investigated dc grid has two units of converters described in Fig. 2, which are the main building blocks of the dc microgrid in Fig. 1. Here, a pure dc source is connected via a step-up (boost converter) at the source side and load side with a step-down (buck converter). A dc link capacitor is also used to connect two converters and build a small-scale dc microgrid.

IV. MODELLING OF A DC GRID AND METHODOLOGY

A. MATHEMATICAl MODEL OF THE DC GRID

The DC grid can be expressed by a set of linear differential equations which can be written in the following form of a generalized linear system.

\[ x = Ax + Bu \]

where:

- \( A \) is a \( n \times n \) state matrix, and \( n \) is the number of states;
- \( B \) is the input matrix with a dimension of \( n \times 2 \);
- \( C \) is the output matrix with a dimension of \( 1 \times 4 \); \( x \) is a state vector, \( x \in \mathbb{R}^n \); \( x = [i_{L1}, V_{c1}, i_{L2}, V_{c2}]^T \), \( u \) represents the control input vector, \( u \in \mathbb{R}^2 \); \( u = [d_{\text{boost}}, d_{\text{buck}}]^T \); \( y \) is called the output vector, \( y \in \mathbb{R} \).

The investigated dc grid can be represented in a state-space form by (1), where \( L_1 \) and \( R_1 \) are respectively the source converter (boost converter) inductance and resistance; \( C_i \) is the filter capacitance; \( i_{L1} \) is the inductor current in the boost converter; \( V_{c1} \) is the capacitor voltage in the boost converter; \( i_{L2} \) is the inductor current in the buck converter; \( V_{c2} \) is the capacitor voltage in the buck converter; \( d_{\text{boost}} \) and \( d_{\text{buck}} \) are...
respectively the duty cycle of the boost and buck converters; \( V_o \) is the linearized voltage at the operating point.

**B. OVERVIEW OF THE LQR CONTROLLER**

The Linear Quadratic Regulator (LQR) is an optimal control scheme which assists in operating a dynamic system at a minimum cost. The objective of the LQR controller is to generate an optimal gain matrix \( K \) in such a way that the objective function is minimum. The overall aim of the LQR controller is to ensure the stability and robustness of the system. A block diagram of the proposed LQR controller for the small scale dc microgrid is presented in Fig. 3. First block which is shown in purple color is the investigated dc microgrid and the second block is the control block which simultaneously control the duty cycle of the associated inverters.

![Block diagram of LQR controller in investigated dc microgrid.](image)

**FIGURE 3.** Block diagram of LQR controller in investigated dc microgrid.

**C. DESIGN OF THE PI CONTROLLER**

To fix and regulate the output voltage, a single variable Proportional Integral (PI) controller is considered in this investigation. The state-space model of the PI controller can be written as

\[
\frac{d\beta}{dt} = [V_{\text{dcref}} - V_{\text{out}}] [\beta] \\
d = K_p (V_{\text{dcref}} - V_{\text{out}}) + K_i \beta
\]

where \( K_p \) and \( K_i \) are respectively the proportional and integral gains of the PI controller. \( \beta \) is introduced to represent the state vector of the integrator. To construct a prototype of the dc microgrid, the boost and buck converters are first designed individually in a Matlab Simulink platform. A conventional proportional and integral controller is then selected on the basis of a root locus, phase margin (PM), step response, and gain margin (GM). According to [23], to ensure the system stability, PM should be higher than 60 degrees and GM should be higher than 6 dB. The values of proportional (P) and integral (I) gains respectively (i.e., \( K_p = 0.0011262 \) and \( K_i = 1.73322185 \)) are selected, based on PM = 85 degrees and GM = 16dB 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, which is shown in Fig. 4.

**D. DESIGN OF THE LQR CONTROLLER**

The LQR controller can be described in a linear state-space form as shown in (1). The objective of the proposed controller is to mitigate the severity of the disturbance and to maintain the dc bus voltage at a set point which can be represented as

\[
y = CX = V_{\text{dc}}
\]

\[
\Delta y = V_{\text{dcref}} - V_{\text{dc}}
\]

where \( V_{\text{dc}} \) is the dc link voltage and \( V_{\text{dcref}} \) is the desired voltage. As previously discussed, during a disturbance, the duty cycle of the conventional controller shows abnormal behaviours. Hence, controlling the duty cycle during disturbance can be formulated as

\[
\Delta u^* = [\Delta d_{\text{boost}} \Delta d_{\text{buck}}]
\]

where \( \Delta u^* \) denotes as an incremental change in the controller input; \( \Delta d_{\text{boost}} \) and \( \Delta d_{\text{buck}} \) represent changes in the duty cycle in the boost and buck converters respectively. To maintain the dc bus voltage in a particular setpoint, an optimal gain is extracted as follows:

\[
K^* = [K_1 \ K_2]
\]

where \( K_1 \) and \( K_2 \) are respectively the new extracted gain to control the boost and buck converter; Since the overall intent of this investigation is to improve the stability of dc bus voltages, the objective of the LQR controller is selected to minimise the cost function \( J \), as follows:

\[
J = \sum_{i=0}^{N} (\Delta y^T Q \Delta y + \Delta u^T R \Delta u) \]

where \( Q \) is the positive definite symmetry matrix, \( u \) is the controller input, \( y \) is the output variable and \( R \) is the real positive definite symmetry matrix. \( Q \) gives a weight to the state, \( x(t) \) and \( R \) give a weight to the control signal, \( u^*(t) \). The value of \( Q \) and \( R \) are selected to minimise the cost function \( J \), and the value must be within the range of \( Q' \geq 0 \) and \( R' > 0 \). This can be expressed as

\[
Q = C^T Q C
\]

Here, \( Q \) is the weight of the plant output. The optimal feedback control law can be written as follows:
\[ \Delta u = -k \Delta y \]  

(9)

\( K \) is the optimal gain matrix that defines a control signal on the basis of the solution of Riccati differential (RD) equation. The optimal gain \( K \) and Riccati differential equation are respectively given by (10) and (11) as

\[ K = R^{-1} B^T P \]

(10)

\[ A^T P + PA - PB R^{-1} B^T P + Q = 0 \]

(11)

Thus, the matrix of the system can be written as

\[ A_{\text{closedloop}} = A - BK \]

(12)

In this case, a completely new approach of the multivariable LQR controller is proposed. To minimize the cost function \( J \), a cheap control approach is considered; and after tuning (i.e., applying a trial and error method), the value of \( Q \) and \( R \) are respectively selected as \( Q = 10 \) and \( R = 0.1 \).

V. SIMULATION RESULTS

This section presents the impact of the conventional controller and the proposed controller on a dc bus in the dc grid with various aspects. The proposed method is then validated through simulation studies in this section as well.

A. PERFORMANCE OF SINGLE VARIABLE CONVENTIONAL PI CONTROLLERS

In this study, a dc microgrid is investigated considering two units of dc/dc converters along with a traditional PI controller, as shown in Fig. 4. The dc/dc step-up converter is considered for the source side, whereas the dc/dc step-down converter is selected for the load side. The parameters of the converters are given in TABLE 1.

| TABLE 1 | PARAMETERS OF THE DC-DC CONVERTERS |
|---------|-----------------------------------|
| Boost converter | Buck converter |
| \( V_s = 30 \text{V} \) | \( V_s = 40 \text{V} \) |
| \( L_1 = 147 \text{e}^{-4} \text{H} \) | \( L_1 = 0.044 \text{H} \) |
| \( V_o = 40 \text{V} \) | \( V_o = 20 \text{V} \) |
| \( R_1 = 75 \Omega \) | \( R_1 = 75 \Omega \) |
| \( D = 0.5 \) | \( D = 0.5 \) |
| \( C_1 = 500 \text{e}^{-4} \text{F} \) | \( C_2 = 470 \text{e}^{-4} \text{F} \) |

FIGURE 4. Investigated dc microgrid with a conventional PI controller.

The output of PV’s can be fluctuated with respect to the whether conditions, hence, this uncertainty has been considered in this investigation. The change of loads is also taken into consideration. Hence, the disturbances of the source and load are purposely imposed to see their impacts on the dc bus, as illustrated in Figs. 5-7.

Fig. 5 shows the common dc bus voltage with small to moderate disturbances (i.e., 25% V drop and 50% V drop) between 0.5 sec and 2 sec, respectively at the source side. Fig. 5(a) depicts the dc bus voltage due to the effect of a small disturbance (7.5 V drop). It is observed that the bus voltage fluctuates between 30 V to 65 V during the disturbance time (0.5 sec to 2 sec) and then decayed to the pre-disturbance value after the clearance of the disturbance. As shown in Fig. 5(b), due to a moderate disturbance (15 V drop), the dc bus voltage declines from 40 V to around 18 V at 0.5 sec and 2 sec, rises from 40 V to approximately 105 V and then settles down with a negligible amount of oscillation at the dc bus. In both cases, significant overshoot along with resonance in the dc bus is observed. In a power system, load uncertainty is pervasive and these uncertainties can lead to voltage changes.

To closely examine the effect of load disturbances in a DC grid, the impedance of the load is reduced from 75 \( \Omega \) to 37 \( \Omega \) (50% disturbance) and 75 \( \Omega \) to 56.25 \( \Omega \) (25% disturbance), as shown in Fig. 6. This figure also shows the impact of sudden load changes on the dc bus. In both cases, a negligible amount of power oscillation is observed without any overshoot or resonance peak. In the dc grid, in worst cases, the source and load side disturbances might happen concurrently. To investigate the impact of both side disturbances on the dc bus, a small type disturbance (25 % source voltage and the reduced load) and a moderate disturbance (50 % source voltage and the reduced load) are considered. Figs. 7(a)-(b) show the impact of both side disturbances concurrently in both sides of the converters on the dc bus.
After being subject to the disturbance at 0.5 sec, the impedance of the load is decreased in the buck converter and the voltage is reduced in the boost converter, an amount of voltage oscillation is introduced at the dc bus. In both cases, high overshoot (20 V-105 V) along with resonance peak is observed. The above results show that disturbances can modify the operating point of the controller. As a result, voltage oscillation in the grid is possible and the system might become unstable accordingly. Overall, power oscillation is found in case of a PI controller equipped with a boost-buck converter in the dc grid.
B. IMPEDANCE SCANNING AND FFT ANALYSIS AT A COMMON DC BUS

It is presumed that power oscillation at a dc bus occurs due to the interaction between controllers or resonance frequencies. To find out the cause of the power oscillation in dc bus, impedance analysis and fast Fourier transform (FFT) analysis are conducted and depicted in Fig. 8. The analytical expression of total impedance $Z_t$ can be expressed as

$$Z_t = \frac{Z_{ocl} \times Z_{ul}}{Z_{ocl} + Z_{ul}}$$  \hspace{1cm} (13)

where, $Z_{ocl}$ is the output impedance of the closed-loop boost converter and $Z_{ul}$ is the closed-loop input impedance from the buck converter. Accordingly, the closed-loop output impedance can be expressed as follows:

$$Z_{ocl}(s) = \frac{Z_o(s)}{1 + T(s)}$$  \hspace{1cm} (14)

where $Z_o(s)$ is the open-loop output impedance of the boost converter, which can be expressed as

$$Z_o(s) = \frac{s^2 + s\left(C_i R_i \left(1 + D^2\right) + L_i R_i \times D^2\right)}{L_i \times C_i \times R_i}$$; and $T(s)$ is the loop gain of the boost converter and it can be written as

$$T(s) = \left(K_p + \frac{K_i}{s}\right) \times \left(\frac{V_{in}}{(1-D)^2}\right) \times \left(1 - s \frac{L_i}{(1-D)^3 \times R_i}\right)$$

$$\times \left(\frac{L_i \times C_i}{(1-D)^2}\right) \times \left(\frac{1}{s^2 + \frac{1}{(C_i \times R_i) \times \left(1 - \frac{(1-D)^2}{L_i}ight)}} + \frac{(1-D)^2}{L_i \times C_i}\right)$$

The closed-loop input impedance from the load side buck converter can be described as

$$Z_{cl}(s) = \frac{Z_i(s) \times R_{cl} \times (1 + T(s))}{R_{cl} + Z_i(s) - D^2 \times T(s)}$$ \hspace{1cm} (15)

where $Z_i(s)$ is the open-loop input impedance of the buck converter, which can be expressed as

$$Z_i(s) = \frac{s^2 \times L_i \times C_i \times R_{cl} \times D^2}{D^2 \times (1 + s R_{cl} C_i)}$$; and $T(s)$ is the loop gain of the buck converter, which can be written as

$$T(s) = \left(K_p + \frac{K_i}{s}\right) \times \left(\frac{V_{in}}{L_i \times C_i \times L_c \times C_L \times R_{CL} \times \left(1 + \frac{1}{C_L \times R_{CL}}\right)}\right) \times \left(1 + \frac{1}{L_i \times C_i}\right)$$

FIGURE 8. (a) Impedance frequency response which can be seen from the dc link (b) FFT on the dc bus with PI controllers.

Fig. 8(a), shows the impedance frequency response $Z_t$, which can be seen from the dc link. It is revealed that except the resonance peak at 294 Hz, the total magnitude is under the satisfactory state. To investigate the resonance frequency on the dc link, an AC voltage source of 1 V and 294 Hz is added into the dc source. An FFT analysis is then carried out on the dc bus voltage. It can be seen from Fig. 8(b) that the amplitude of the voltage is steady till 150 Hz. Thereafter, a resonance peak is perceived nearby 294 Hz, which is similar to the impedance scanning. Since then it falls gradually and finally keeps steady at around 480 Hz.
FIGURE 9. Impact of voltage disturbances on the source side; considering a proposed LQR controller for (a) 25% and (b) 50% voltage disturbances.

C. PERFORMANCE OF THE PROPOSED MULTIVARIABLE LQR CONTROLLER ON THE STABILITY AT A DC BUS

In this case study, the proposed multivariable LQR controller is designed in MATLAB. A time-domain simulation is carried out and the results are then depicted in Figs. 9-11. A similar type of disturbances presented in Section 5.1 is applied to the system with a newly designed LQR controller. Figs. 9(a) and (b) present a dc bus voltage when small and moderate disturbances respectively are applied to the source side of the converter. It can be seen that during the disturbance, the bus voltage fluctuates between 40 V and 38 V, which has been zoomed out and circled in red colour. It is also noticed that, after eliminating the disturbance, the bus voltage returns to a stable state.

Figs. 10 (a) and (b) show the dc bus voltage when small and moderate disturbances are applied to the buck converter separately and both sides of the converter, respectively. A negligible amount of power oscillation is observed without any overshoot. It can be noticed that during the disturbance, the voltage fluctuates approximately between 40 V and 36 V. After the disturbance is removed, the bus voltage comes back to a reasonable steady-state condition without any overshoot or significant power oscillation. It is also noticed that overshoot is completely disappeared at the dc bus. To this end, an FFT analysis is carried out on the bus voltage and plotted in Fig. 11.

The total harmonic distortion (THD) in dc bus voltage is found at about 0.07%, which is significantly lower than a conventional PI controller, as shown in Fig. 8(b).
Finally, a comparison between PI and LQR controllers is represented in Fig. 12. A 50% voltage disturbances have been applied on the both model and the key results are highlighted and circled, as shown in Fig. 12. It is clearly noticed that the proposed method can reduce the overshoot and can provide stable and oscillation free dc bus voltage against disturbances. It is clear from the above result that multivariable LQR controllers produce a better performance in terms of stable and oscillation free dc bus voltage when compared to the conventional controller.

VI. CONCLUSION

In this paper, firstly, the notion of high-frequency power oscillation and resonance in a dc microgrid has been discussed. The impact of disturbances at the source and load sides along with conventional PI controllers on a common dc bus in a dc microgrid has been comprehensively analysed. From the analysis, it has been found that the conventional PI controller cannot handle even moderate disturbances in the dc microgrid. Significant overshoot along with immense power oscillation is observed at dc bus. An undamped oscillation is observed after having a series of disturbances. This oscillation could be a recipe for resonance, which could cause the system into an unstable condition and blackout. It is also noticed that the impact of disturbances on the source side is more influencing compared to the load side disturbance. Secondly, to minimize the overshoot and power oscillation in a dc microgrid, a multivariable controller is designed, and similar types of disturbances are applied to the same network to check the performance of the proposed controller. It is observed that the proposed controller produce better results in regards to overshoot, resonance, and power oscillation. Hence, the proposed method can enhance the stability of the system as it eliminates power oscillation at the dc bus.

In future, a multi unit of converters based DCMG will be designed and investigated with respect to various uncertainties. Considering the uncertain operating conditions of DC microgrids, advanced control may be used in the future. The effect of the advanced control on the DCMG will be assessed and reported in the future as well.

REFERENCES

[1] S. Augustine, J. E. Quiroz, M. J. Reno, and S. Brahma, "DC Microgrid Protection: Review and Challenges," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States)2018.
[2] S. Sarangi, B. K. Sahu, and P. K. Rout, "A comprehensive review of distribution generation integrated DC microgrid protection: issues, strategies, and future direction," International Journal of Energy Research, vol. 45, no. 4, pp. 5006-5031, 2021.
[3] S. Augustine, M. J. Reno, S. M. Brahma, and O. Lavrova, "Fault Current Control and Protection in a Standalone DC Microgrid Using Adaptive Droop and Current Derivative," IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020.
[4] M. Habibullah, N. Mithulananthan, R. Shah, and K. Bhukmittitipich, "Study of Voltage Oscillation in Multi-Converter Based DC Microgrid," in 2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES), 2020, pp. 316-321: IEEE.
[5] A. Chandra, G. Singh, and V. Pant, "Protection techniques for DC microgrid-A review," Electric Power Systems Research, vol. 187, p. 106439, 2020.
[6] D. Kumar, F. Zare, and A. Ghosh, "DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects," IEEE Access, vol. 5, pp. 12230-12256, 2017.
[7] M. Habibullah, N. Mithulananthan, K. N. Bhukmittitipich, and M. Amin, "A Comprehensive Investigation on High-Frequency Oscillation in DC Microgrid," IEEE Access, vol. 9, pp. 54850-54861, 2021.
[8] M. Habibullah, "Modelling and Design of DC Microgrid with Renewable Energy for Stability Analysis," 2021.
[9] C. Li, Y. Yang, T. Dragicevic, and F. Blaabjerg, "A New Perspective for Relating Virtual Inertia with Wideband Oscillation of Voltage in Low-Inertia DC Microgrid," IEEE Transactions on Industrial Electronics, 2021.
[10] G. Lin, W. Zuo, Y. Li, J. Liu, S. Wang, and P. Wang, "Comparative analysis on the stability mechanism of droop control and VID control in dc microgrid," Chinese Journal of Electrical Engineering, vol. 7, no. 1, pp. 37-46, 2021.
[11] M. Habibullah, N. Mithulananthan, F. Zare, and R. Sharma, "Impact of Control Systems on Power Quality at Common DC Bus in DC Grid," in 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), 2019, pp. 411-416.
[12] G. Lin et al., "A virtual inertia and damping control to suppress voltage oscillation in islanded DC microgrid," IEEE Transactions on Energy Conversion, 2020.
[13] M. Davari and Y. A.-R. I. Mohamed, "Robust Droop and DC-Bus Voltage Control for Effective Stabilization and Power Sharing in VSC Multiterminal DC Grids," IEEE Trans. Power Electron, vol. 33, no. 5, pp. 4373-4395, 2018.
[14] Z. Wang, S. Li, J. Wang, and Q. Li, "Generalized proportional integral observer based backstepping control for DC-DC buck converters with mismatched disturbances," in Industrial Technology (ICIT), 2016 IEEE International Conference on, 2016, pp. 1783-1789: IEEE.
[15] H. Setiadi, A. U. Krismanto, N. Mithulananthan, and M. Hossain, "Modal interaction of power systems with high penetration of renewable energy and BES systems," *International Journal of Electrical Power & Energy Systems*, vol. 97, pp. 385-395, 2018.

[16] N. Rashidirad, M. Hamzeh, K. Sheshyekani, and E. Afjei, "High-Frequency Oscillations and Their Leading Causes in DC Microgrids," *IEEE Transactions on Energy Conversion*, vol. 32, no. 4, pp. 1479-1491, 2017.

[17] R. Shah, N. Mithulananthan, A. Sode-Yome, and K. Y. Lee, "Impact of large-scale PV penetration on power system oscillatory stability," in *IEEE PES general meeting*, 2010, pp. 1-7.

[18] S. Lamichhane and N. Mithulananthan, "Influence of wind energy integration on low frequency oscillatory instability of power system," in *Power Engineering Conference (AUPEC), 2014 Australasian Universities*, 2014, pp. 1-5.

[19] M. Amin, M. Molinas, and J. Lyu, "Oscillatory phenomena between wind farms and HVDC systems: The impact of control," in *Control and Modeling for Power Electronics (COMPEL), 2015 IEEE 16th Workshop on*, 2015, pp. 1-8: IEEE.

[20] M. Habibullah, N. Mithulananthan, F. Zare, and D. S. Alkaran, "Investigation of power oscillation at common DC bus in DC grid," in *2019 IEEE International Conference on Industrial Technology (ICIT)*, 2019, pp. 1695-1700.

[21] Y. Wang, Q. Song, Q. Sun, B. Zhao, J. Li, and W. Liu, "Multilevel MVDC link strategy of high-frequency-link DC transformer based on switched capacitor for MVDC power distribution," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 4, pp. 2829-2835, 2017.

[22] M. Hamzeh, A. Ghazanfari, Y. A.-R. I. Mohamed, and Y. Karimi, "Modeling and design of an oscillatory current-sharing control strategy in DC microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6647-6657, 2015.

[23] X. Feng, J. Liu, and F. C. Lee, "Impedance specifications for stable DC distributed power systems," *IEEE Trans. Power Electron.*, vol. 17, no. 2, pp. 157-162, 2002.