

Secondary Voltage Control in a Hybrid Microgrid

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A Compared to individual DC or AC microgrids, Hybrid Microgrids (HMGs) are more efficient and inexpensive due to the
B elimination of multiple DC-AC-DC conversions. In HMGs, where AC loads are supplied by a DC link, load demand disturbance
S has direct negative effects on the DC link voltage. In this study, primary and secondary controllers are applied to realize suitable
T operation conditions and control the microgrid converters. Each converter has a primary controller to compensate for the
R demand power fluctuations. A secondary controller is also designed for extra demand varieties to send the proper control signals
A to the primary controllers. The expressed capability of the primary controllers can be obtained by designing a simple and robust
C secondary controller. Hence, the effects of demand fluctuations are eliminated and the system is stabilized. The overall state
T space model of the system is conducted for stability analysis. To demonstrate the proposed controller efficiency, a prototype
HMG is modeled and simulated. The stability analysis reveals that the system is stable when the secondary controller tracks the
error signal of the DC link. Simulation results show that the proposed method could efficiently manage the AC side voltage under
load fluctuations.

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I. INTRODUCTION

In recent years, scientists have focused on using renewable sources due to the depletion of fossil fuels and the environmental pollution. In addition, demand for electric power as a clean and efficient type of energy has significantly increased [1–3]. As the consumption of the electric power goes up, the robust management of the electrical distribution system becomes more essential for increasing the stability and efficiency of the grid. Among various systems and techniques, microgrid (MG) is a new and efficient system for the management of the widespread grid. Indeed, this system consists of a block of smart grid in which distributed energy sources (DESSs) are widely used to supply required electric power [4–7]. These small-scale systems have many advantages such as reducing environmental pollutions, decreasing electric energy cost, increasing the stability of power systems, and improving the quality of electric power [8–10].

MGs can operate in two operating modes: autonomous and

grid-connected operation modes. The ability to switch between these two operating modes considerably improves the stability and reliability for consumers and power system operators. Generally, MGs are classified in three categories: alternative current (AC), direct current (DC), and hybrid AC-DC [11–13]. While DC MGs can be linked to DC output sources (e.g., PVs and energy storage systems) and support DC electronic loads with less conversion and loss, they do not deal with some challenges in AC MGs such as synchronization, frequency control, and reactive power management [14–17].

Hybrid microgrids (HMGs) have been subject to extensive research in the literature recently [18,19]. HMGs consist of both AC and DC networks with various topologies [1,15,17,20,21] while the advantages of both systems are preserved. MGs are connected to electrical grid via point of common coupling (PCC) by static switches (SS).

In order to secure operation, different control loops are used, and they are classified into four levels: local, secondary, emergency/central and global control. Local control is a decentralized control with the lowest control level in MG. Voltage and current control loops for small generators or controllable loads are known as good samples for this type. If a

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disturbance happens out of the operational range of the local control loop, a secondary control loop is applied to adjust several micro-sources or controllable loads. Thus, the system operational indexes are kept within a reasonable range. The central control loop is used to connect/disconnect an MG with other MGs or electrical grids.

Global control is responsible for policy making and interchanging economic power between MG and other MGs or electrical grids [4]. In most recent studies on HMGs [21–23], DC loads and DC electric power sources with energy storage systems are in DC side while AC loads and AC electric power sources are in AC side. Two AC and DC grids are connected to each other via a main bidirectional converter. Previous studies have focused on appropriate control methods for the main converter of MG. However, it is difficult to separate both DC and AC loads and sources and it needs to spend an extra cost.

DC and AC load demands are connected to the electric power sources via a DC link [18,24]. The main disadvantage of the above-mentioned tasks is the lack of a proper controller on the DC voltages link. Due to the changes in the production and consumption pattern, the DC link voltage also varies. In the above references, rectification is done by power diodes without having control over the DC link.

In several recent works [25–28], researchers have represented the MGs state space to express the control method with stability and sensitivity analysis. Generally, the stability analysis is

necessary for the expression of any control method in the MGs because each control method contributes to system stability or improves the performance of the system. Indeed, the stability analysis on the MGs can introduce a clear understanding of the performance of the controller. Hence, the present work focused on the HMG state space modeling.

This paper investigates an HMG to provide appropriate operating conditions for the system via local and secondary control loops. The applied topology is shown in Fig. 1. The output of the distributed energy resources is collected in a Distributed Resource Center (DRC), and then the output of DRC is available for consumers in DC form. As shown in Fig. 1, consumers in the power grid are divided into two main categories: urban consumers (residential and commercial) and industrial consumers. According to recent studies, the majority of residential and commercial operate in DC form. In order to reduce unnecessary power conversions, urban electric grid and industrial centers which often use three-phase power are developed in DC and AC forms, respectively. Each of the power converters has its own proper local control loop. In addition, the secondary control loop is used to protect and maintain variables of the system under different operations. In order to interchange economic power, the emergency/central control loop is employed. It is responsible to maintain grid/microgrid stability and secure economic power transmission.

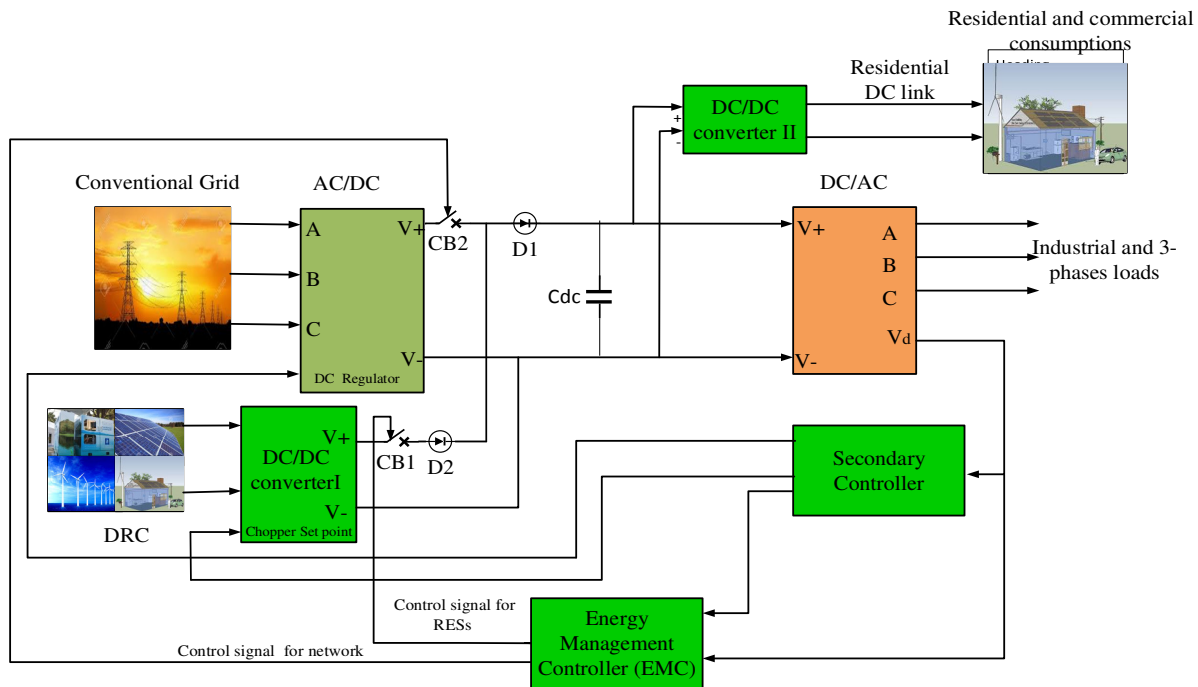


Fig. 1. Hybrid AC-DC microgrid topology

Since AC consumers are fed by a DC link in this type of topologies, any change in energy consumption influences the DC link voltage directly, and hence the voltage of the consumer side will change uncontrollably.

The main issue for using HMGs is an efficient control system which ensures the stability of the MGs in various conditions. Hence, the main scope of the present study is to present a simple and appropriate control system that reduces the effect of power

demand fluctuations on the voltage of the AC demand side.

II. SYSTEM CONFIGURATION AND MODELING

Grid configuration is of paramount importance in system modeling. In this paper, the outputs of the distributed energy resources (DERs) are collected in a DRC. The output voltages of the DRC are DC. An AC/DC converter is connected to the DC link directly and the output of the DRC is connected to the DC

link by a boost chopper. Then, three-phase consumers are connected at the end of DC link by a three-phase DC/AC inverter.

Each converter locally controls its output based on the given set point. The proposed secondary controller was designed to determine the set point of the two main converters, AC/DC converter, and boost chopper. The performed case study and their controllers are shown in Fig. 2.

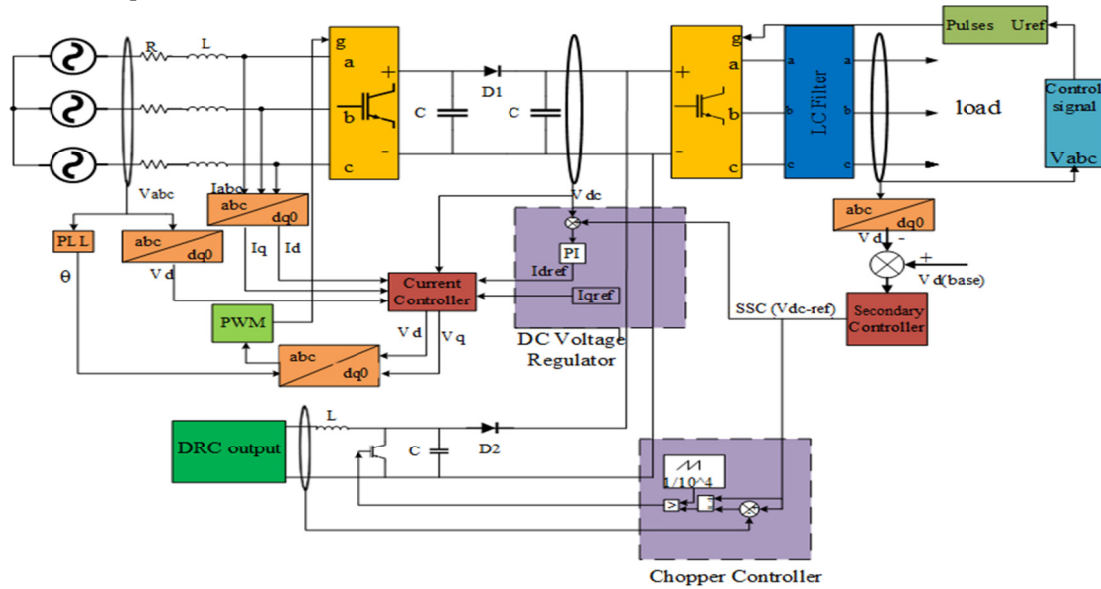


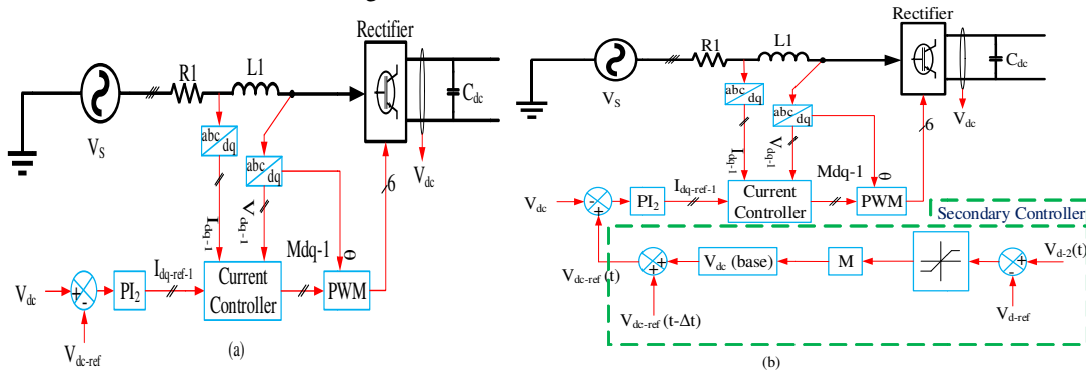
Fig. 2. Performed case study with their controllers

The HMG shown in Fig. 2 consists of four controllers: A) an AC/DC converter controller, B) a boost chopper controller, C) a secondary controller, and D) an inverter controller.

A. AC/DC converter controller

As mentioned, the three-phase conventional grid is rectified by Isolated Gate Bipolar Transistors (IGBTs) via an AC/DC converter. In several studies, just diodes have been used as AC/DC converters, and consequently, there is no control on the output voltage [18,24]. In this paper, two main controllers have been used to control the DC link voltage. The DC voltage regulator is one of the main controllers for ensuring a load

following the DC link voltage. Fig. 3 depicts the conventional grid and AC/DC converter with its controller. As shown in Fig. 2, a three-phase power source is converted to DC voltage by using IGBTs, and the DC regulator produces a pattern of IGBT switching according to its set point. The DC regulator includes two units: a) a DC voltage regulator, and b) a current regulator. In the DC voltage regulator block, the DC link voltage is compared to its set point, and then the error signal passes through the PI controller.



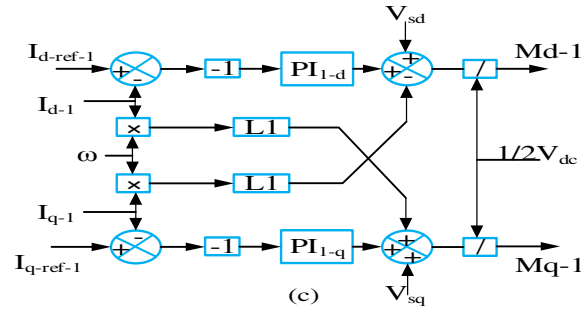


Fig. 3. Block diagram of (a) the conventional rectifier with a constant value DC-link voltage regulator circuit, and (b) the modified rectifier with a dynamic DC-link voltage regulator circuit, and (c) the current controller scheme.

The output signal of the DC voltage regulator is a current reference for the current regulator. The structure of the current controller in rectifier is the same as the current controller in the inverter. The direction of the current is assumed positive when the current is sent from DC to AC side. However, the direction of the current in rectifiers is the opposite of that in the inverters [26,29]. Also, the output of the current regulator produces a reference

signal V_{dq} , and it would be converted to three-phase. The IGBT switching is done by Pulse Width Modulation (PWM).

B. Boost chopper controller

Chopper is a DC/DC converter with variable output voltage capability which can be applied in buck, boost and buck-boost configurations. The chopper used in this paper is a boost one which converts 200V output voltage level of DRC into 850 V DC link. The boost chopper circuit is displayed in Fig. 4.

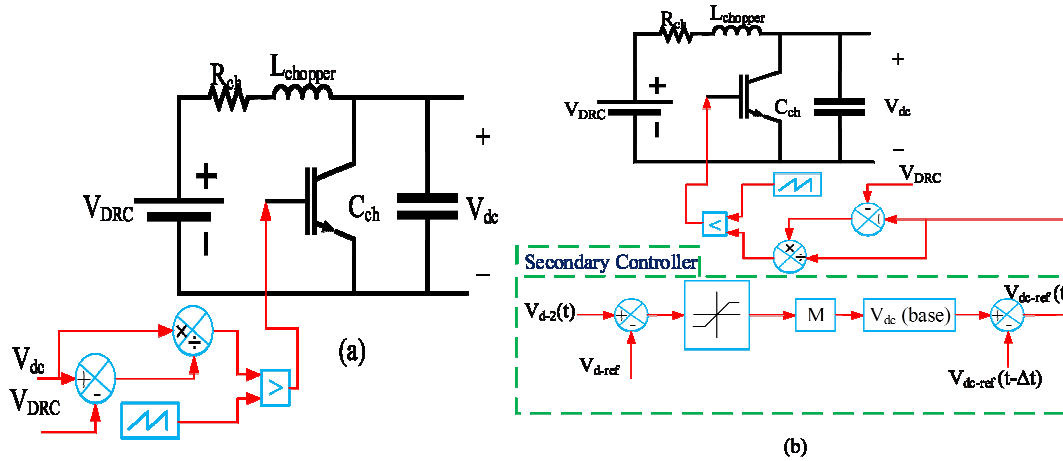


Fig. 4. Block diagram of (a) the conventional boost chopper with constant output value (constant duty ratio) circuit, and (b) the modified boost chopper with variable output (variable duty ratio).

As shown in Fig 4.(a), the duty ratio of IGBT will be constant due to specified input and output voltage. But, in Fig 4. (b) the boost chopper output voltage will be variable with AC side load demand. In normal conditions, the DC link voltage value is 850 V. The increment (reduction) of consumption in the AC side may lead to a reduction (increment) in the load voltage. Hence, AC side voltage is compared with its reference, and the output of the secondary controller (is a DC link reference) is sent to the boost chopper for determining the IGBT duty ratio. The output voltage of boost chopper is calculated by:

$$V_{output} = \frac{V_{input}}{1-K} \quad (1)$$

The input voltage and DC link voltage are 200V and 850V, respectively. In addition, K as the duty ratio would be 76.5%.

Having the time-varying DC link voltage is the basic-principle in our research. Hence, for a variable output voltage, variable K is required. Using Eq. (1), the following equation is achieved.

$$K_{variable} = \frac{V_{setpoint} - V_{input}}{V_{setpoint}} \quad (2)$$

where $K_{variable}$ is the IGBT duty ratio and $V_{setpoint}$ is equal to V_{output} . The output voltage of the boost chopper is determined by the secondary controller. $V_{setpoint}$ is the output signal of the secondary controller. V_{input} is DRC constant voltage (200V).

C. Secondary controller

The power balancing and DC link voltage dynamics are described below. The network and output of DRC are the electric power sources in this work.

$$\frac{C_{dc}}{2} \frac{dV_{dc}^2}{dt} = P_{IN} - P_{VSI} \quad (3)$$

where P_{IN} is the injection power from sources to system and P_{VSI} is the sending power to three-phase consumers by the inverter. The sending power by the inverter is equal to the power demand and power losses in the AC side as given in (4).

$$P_{VSI} = P_{LINE} + P_{LOAD} \quad (4)$$

In distributed networks, power losses can be neglected when

$$\frac{X_{LINE}}{R_{LINE}} \geq 1. \quad (5)$$

As mentioned, the injection power to the system is composed of the electrical network by the rectifier and DRC output by the boost chopper.

$$P_{IN} = P_{rectifier} + P_{DRC} \quad (6)$$

In dq frame, the power injection from the rectifier can be shown in the following form.

$$P_{rectifier} = \frac{3}{2} (V_d I_d + V_q I_q) \quad (7)$$

$$Q_{rectifier} = \frac{3}{2} (-V_d I_q + V_q I_d) \quad (8)$$

Assuming $V_q = 0$ for obtaining appropriate control strategies, we can consider $V_q = 0$; therefore, (7) and (8) can be expressed by (9) and (10). As a result, the active power is controlled by I_d and the reactive power with I_q . On the other hand, I_d and I_q are controlled by I_{dq_ref1} as shown in Figures 2 and 3(b). Hence, with DC link voltage control the I_{dq_ref1} signal is created and I_d and I_q will then be controlled. In the other word, the active and reactive power of rectifiers can be controlled by control of the DC link voltage.

$$P_{GRID} = \frac{3}{2} (V_d I_d) \quad (9)$$

$$Q_{GRID} = \frac{3}{2} (-V_d I_q) \quad (10)$$

The injected power from the DRC to the system can be expressed by (11). The output active power from boost chopper is controlled by the DC link voltage.

$$P_{DRC} = (V_{dc} I_{out-chopper}) \quad (11)$$

According to the above description, by controlling DC link voltage, the active power from the rectifier and boost chopper is controlled.

In HMGs with constant DC regulator, the DC link voltage does not change with changes in load demand. However, the AC side consumer voltage is changed because the DC link could not supply the power demand. In this study, the DC link has a dynamical DC voltage regulator, and a simple and robust algorithm is developed to damp the changes in the consumer

voltage due to the changes in load demand. The flowchart of the proposed algorithm is shown in Fig. 5.

Fig. 5 displays the secondary controller algorithm. After running, the voltage of the system is measured, and V_d is obtained via park transformer, and ΔV_d shown in the flowchart is calculated as follows.

$$\Delta V_d = 1 - V_d \quad (12)$$

If ΔV_d is less than 0.05 pu, DC link voltage will remain constant.

But, if ΔV_d is higher than 0.05 pu, the secondary controller will change the set point value. For example, the load voltage is reduced when the power consumption increases.

In this case, to compensate for the load voltage variation, DC link voltage must increase and vice versa. The DC link voltage percentage is calculated as follows.

$$\%V_{dc(t)} = \%V_{dc(t-\Delta t)} + \Delta V_d M \quad (13)$$

where $\%V_{dc}(t - \Delta t)$ is the percentage of load voltage at time step $(t - \Delta t)$, and $\Delta V_d M$ is the perturbation parameter. M is a constant coefficient to reduce load voltage deviation. As already mentioned, load voltage is inversely proportional to power consumption, and this condition is illustrated in Eq. (12). If the load voltage is increased, the V_d value will exceed 1 pu, and the result of Eq. (12) will be negative. This negative signal will magnify with the impact factor (M) and will be added to the DC link voltage at time step of $(t - \Delta t)$. The DC link voltage will be decreased because the obtained signal is negative. The Signal of Secondary Controller (SSC) obtained by Eq. (13) is multiplied by base DC link voltage. The SSC determines the set point of controllers for the DC regulator and boost chopper. As a result, the DC link voltage is dynamically compensated for when the load demand is changed.

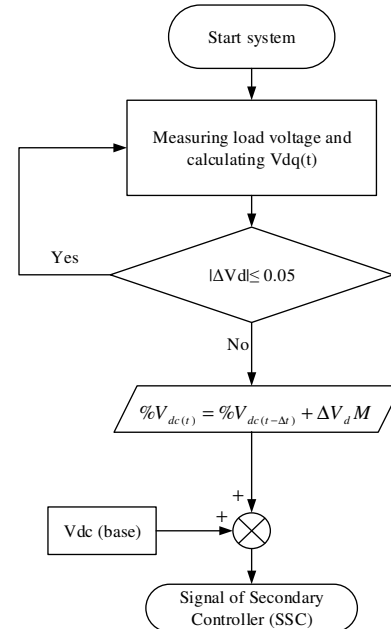


Fig. 5. The proposed secondary control algorithm

D. DC/AC converter controller

Here, we used a Voltage Source Converter (VSI) to convert DC to AC voltage because most consumers are AC type. The VSI configuration and its controller are shown in Fig. 6. On the other hand, an LC filter is used to eliminate the voltage and current ripples.

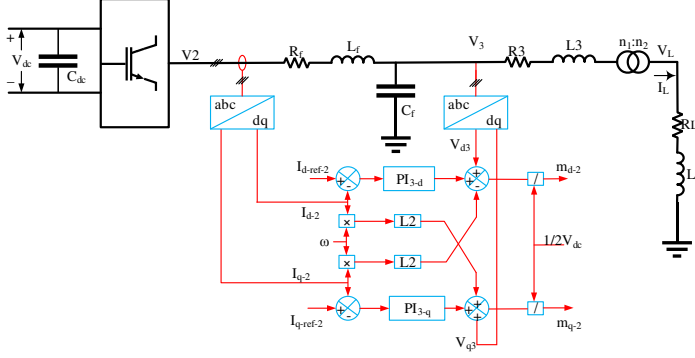


Fig. 6. Voltage Source Inverter (VSI) circuit

As shown in Fig. 6, the output of the inverter controller is a PWM reference signal. The inverter controller is composed of a comparator and a PI controller to remove the error signal. Comparator block compares the load voltage with its reference and produces an error signal.

III. STATE SPACE MODELING

System stability analysis is necessary for any proposed method of control in MGs. Generally, a system is stable when all real values of eigenvalues are negative. In the following, state space equations of the HMG components are provided, and finally, the state space equation is achieved.

A. Rectifier state space

Three-phase grid voltage is rectified by a controllable rectifier. The controllable rectifier introduced in Section II.A has two control loops. First, the DC link voltage is compared with the reference value and the DC error signal is sent to the current controller. Later, the current controller compares the network current with their reference values, and finally, the output signal is sent to the PWM. The following equations are represented in dq-frame:

$$\frac{d}{dt}(I_{d-1}) = \omega_0 I_{q-1} - \frac{R_1}{L_1} I_{d-1} + \frac{1}{L_1} V_{sd} - \frac{1}{L_1} V_{d-2} \quad (14)$$

$$\frac{d}{dt}(I_{q-1}) = -\omega_0 I_{d-1} - \frac{R_1}{L_1} I_{q-1} + \frac{1}{L_1} V_{sq} - \frac{1}{L_1} V_{q-2} \quad (15)$$

The relation between DC link voltage and AC side voltage in dq-frame can be expressed as below.

$$V_{d-2} = \left(\frac{V_{dc}}{2} \right) m_{d-1} \quad (16)$$

$$V_{q-2} = \left(\frac{V_{dc}}{2} \right) m_{q-1} \quad (17)$$

where m_{d-1} and m_{q-1} are the controller output signals, which are sent to the PWM unit.

Hence, the grid rectifier state apace is achieved. The state variables and the system input can be shown as follows:

$$\begin{aligned} x_{rect-1} &= [\Delta I_{d-1} \Delta I_{q-1} \Delta X_{ld} \Delta X_{lq} \Delta X_2]^T; x_{rect-2} = [V_{dc}]^T; \\ x_{rect-3} &= [V_{dc-ref}]^T \\ u_{rect} &= [I_{qref-1}]^T \end{aligned} \quad (18)$$

where, $X_{ld} = \int (I_{dref-1} - I_{d-1}) dt$, $X_{lq} = \int (I_{qref-1} - I_{q-1}) dt$ and $X_2 = \int (V_{dc-ref} - V_{dc}) dt$.

B. Secondary controller variables

The block diagram of the secondary controller described in section II.C can be shown as in Fig. 7. The AC side consumer voltage is compared with the reference value and the error signal is multiplied by $MV_{dc(base)}$ coefficient. The output signal is added to $V_{dc-ref}(t)$ and the DC link voltage is created. The secondary controller equation is defined by Eq. (19).

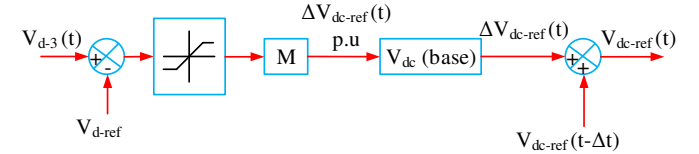


Fig. 7. The secondary controller block diagram

$$V_{dc-ref}(t) = M(V_{d-3}(t) - V_{d3-ref}(t))V_{dc(base)} + V_{dc-ref}(t-\Delta t) \quad (19)$$

Using the concept of derivative, the following equation is achieved.

$$\frac{V_{dc-ref}(t) - V_{dc-ref}(t-\Delta t)}{\Delta t} = \frac{M(V_{d-3}(t) - V_{d3-ref}(t))V_{dc(base)}}{\Delta t} \quad (20)$$

$$\frac{d}{dt}V_{dc-ref}(t) = MV_{dc(base)} \left(-\frac{d}{dt}V_{d-3}(t) + \frac{d}{dt}V_{d3-ref}(t) \right) \quad (21)$$

The states and input variables and state space matrix of the secondary controller are shown below.

$$\begin{aligned} x_{sec-1} &= [\Delta V_{dc-ref}]^T; x_{sec-2} = [\Delta V_{d3}]^T \\ u_{sec} &= [V_{d3-ref}]^T \end{aligned}$$

C. Boost chopper state space

The boost chopper equation is defined as follows.

$$\frac{d}{dt}I_{DRC} = -\frac{R_{ch}}{L_{ch}}I_{DRC} - \frac{1}{L_{ch}}V_{dc} + \frac{1}{L_{ch}}V_{DRC} \quad (22)$$

The states and input variables and state space matrix of boost chopper are shown below.

$$x_{ch-1} = [\Delta I_{DRC}]^T; x_{ch-2} = [\Delta V_{dc}]^T; u_{ch} = [V_{DRC}]^T$$

D. DC link state space model

By using KCL in the DC link, the corresponding equation is derived.

$$I_{conv} + I_{out-chopper} - C_{dc} \frac{dV_{dc}}{dt} - I_{dc} = 0 \quad (23)$$

where I_{conv} , $I_{out-chopper}$, I_{dc} and V_{dc} are the rectifier output current, boost chopper output current, the inverter input current, and the DC link voltage, respectively.

In an ideal converter, the input and output power is equal. Hence, the following equations are defined.

$$P_{in} = P_{out} \quad (24)$$

$$V_{dc} I_{dc} = \frac{3}{2} (V_d I_d + V_q I_q) \quad (25)$$

As the result, the rectifier, inverter and chopper current equations are expressed as follows.

$$I_{conv} = \frac{3}{4} (I_{d-1} m_{d1} + I_{q-1} m_{q1}) \quad (26)$$

$$I_{dc} = \frac{3}{4} (I_{d-2} m_{d2} + I_{q-2} m_{q2}) \quad (27)$$

$$I_{out-chopper} = \frac{V_{DRC}}{V_{dc}} I_{DRC} \quad (28)$$

The above equations are nonlinear, and the linearized dynamic model of the boost chopper is expressed as follows.

$$\Delta I_{out-chopper} = \frac{V_{DRC-nom}}{V_{dc-nom}} \Delta I_{DRC} + \frac{I_{DRC-nom}}{V_{dc-nom}} \Delta V_{DRC} - \frac{V_{DRC-nom} I_{DRC-nom}}{V_{dc}^2} \Delta V_{dc} \quad (29)$$

E. VSI state space model

DC voltage is converted to three-phase consumers by a VSI. According to Fig. 6 for a VSI, the following equations are expressed.

$$\frac{d}{dt} (\Delta I_{d-2}) = \omega_0 I_{q-2} - \frac{R_f}{L_f} I_{d-2} + \frac{1}{L_f} V_{d-2} - \frac{1}{L_f} V_{d-3} \quad (30)$$

$$\frac{d}{dt} (\Delta I_{q-2}) = -\omega_0 I_{d-2} - \frac{R_f}{L_f} I_{q-2} + \frac{1}{L_f} V_{q-2} - \frac{1}{L_f} V_{q-3} \quad (31)$$

The load current and voltage equations are as follows:

$$\frac{d(\Delta I_{d-L})}{dt} = \omega_0 I_{q-L} - \frac{R_2}{L_2} I_{d-L} + \frac{1}{L_2} \left(\frac{N_1}{N_2} \right) V_{d-3} - \frac{1}{L_2} \left(\frac{N_1}{N_2} \right) V_{d-L} \quad (32)$$

$$\frac{d(\Delta I_{q-L})}{dt} = -\omega_0 I_{d-L} - \frac{R_2}{L_2} I_{q-L} + \frac{1}{L_2} \left(\frac{N_1}{N_2} \right) V_{q-3} - \frac{1}{L_2} \left(\frac{N_1}{N_2} \right) V_{q-L} \quad (33)$$

$$\frac{d}{dt} (\Delta V_{d-3}) = \omega_0 V_{q-3} + \frac{1}{C_f} I_{d-2} - \frac{1}{C_f} \left(\frac{N_2}{N_1} \right) I_{d-L} \quad (34)$$

$$\frac{d}{dt} (\Delta V_{q-3}) = -\omega_0 V_{d-3} + \frac{1}{C_f} I_{q-2} - \frac{1}{C_f} \left(\frac{N_2}{N_1} \right) I_{q-L} \quad (35)$$

Using a KVL in the load side for the load voltage, the following equations are obtained.

$$\frac{d(\Delta I_{d-L})}{dt} = \omega_0 I_{q-L} - \frac{(R_2 + R_L) \left(\frac{N_1}{N_2} \right)^2}{QL_2} I_{d-L} + \frac{\left(\frac{N_1}{N_2} \right)}{QL_2} V_{d-3} \quad (36)$$

$$\frac{d(\Delta I_{q-L})}{dt} = -\omega_0 I_{d-L} - \frac{(R_2 + R_L) \left(\frac{N_1}{N_2} \right)^2}{QL_2} I_{q-L} + \frac{\left(\frac{N_1}{N_2} \right)}{QL_2} V_{q-3} \quad (46)$$

where, $Q = \left| 1 + \frac{L_L}{L_2} \left(\frac{N_1}{N_2} \right)^2 \right|$. The state and inputs variables are shown below.

$$x_{inv} = [\Delta I_{d-2} \Delta I_{q-2} \Delta V_{d-3} \Delta V_{q-3} \Delta I_{d-L} \Delta I_{q-L} \Delta X_{3d} \Delta X_{3q}]$$

$$u_{inv} = [I_{d-ref-2} I_{q-ref-2}]$$

D. Overall system state space model

For small signal stability analysis of the system, the overall state space matrices are required. According to the system configuration and their relative state space equations, the overall state matrix can be achieved as

$$A_{sys} = \begin{bmatrix} [A_{rec-1}]_{5 \times 5} & [A_{rec-3}]_{5 \times 1} & [A_{rec-2}]_{5 \times 1} & & & & & & \\ & [A_{sec-1}]_{1 \times 1} & & [A_{sec-2}]_{1 \times 8} & & & & & \\ & & [A_{ch-1}]_{1 \times 1} & [A_{ch-2}]_{1 \times 1} & & & & & \\ & & [A_{dc-link}]_{1 \times 16} & & & & & & \\ & & & & [A_{inv}]_{8 \times 8} & & & & \end{bmatrix}_{16 \times 16} \quad (47)$$

$$B_{sys} = \begin{bmatrix} [B_{rec}]_{5 \times 5} \\ [B_{sec}]_{1 \times 5} \\ [B_{chopper}]_{1 \times 5} \\ [B_{dc-link}]_{1 \times 5} \\ [B_{inv}]_{8 \times 5} \end{bmatrix}_{16 \times 5}$$

IV. FREQUENCY RESPONSE AND STABILITY ANALYSIS

The HMG eigenvalues are shown in Fig. 8. As shown in this figure, all real parts of eigenvalues are located in the left-hand side of the imaginary axis in the presence of a secondary controller.

Root locus and Bode plots are applied for stability analysis using the following transfer function.

$$G_s = \frac{I_{d-1}}{V_{dc} - V_{dc-ref}} \quad (48)$$

where $V_{dc} - V_{dc-ref}$ is the DC error signal.

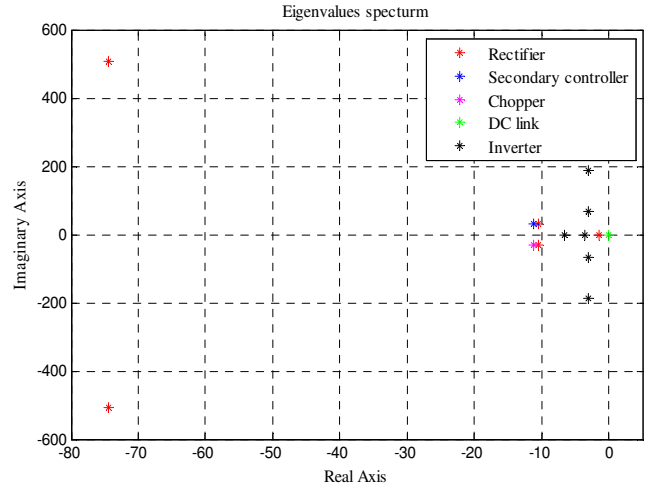


Fig. 8. The HMGs eigenvalues

The root locus and Bode plots are shown in Figs. 9(a) and 9(b), respectively.

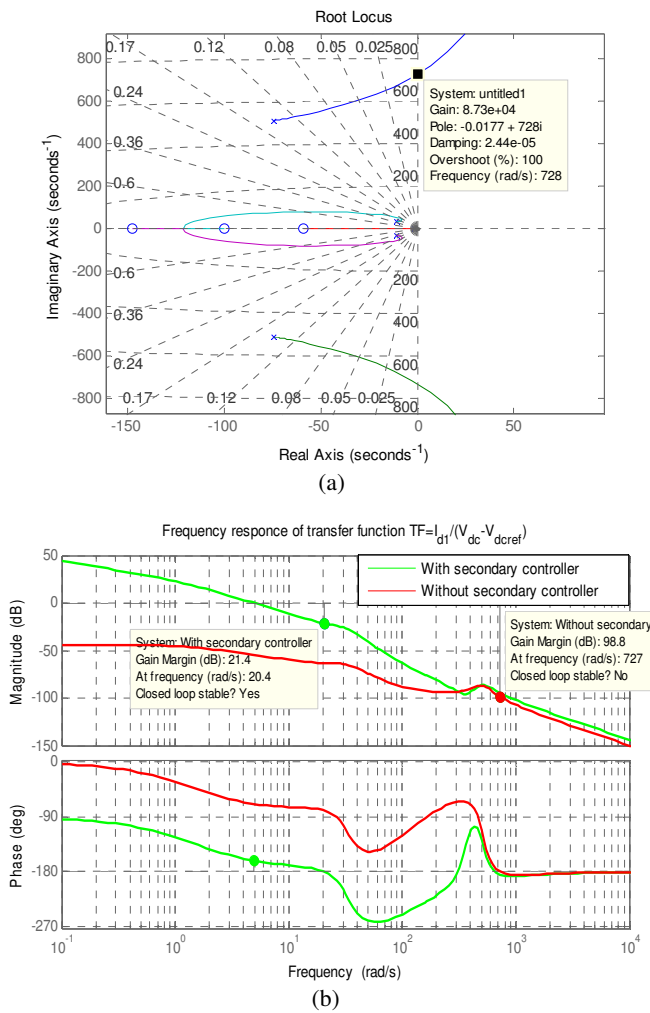


Fig. 9. Small signal rectifier error signal: (a) root locus, (b) Bode plot

As shown in the Bode plot, the closed loop of a specific transfer function without a secondary controller is unstable when the load of the system increases to 1.3 pu, but the system within the secondary controller is stable. The gain margin in the stable system is 21.4 (dB) at frequency 21.4 (rad/sec) and the phase margin is 18.1 (deg) at frequency 4.9 (rad/sec). The root locus plot shows that the system is always stable when the DC gain of the transfer function is less than the critical DC gain (shown in root locus plot and equals to 8.7×10^4). According to the maximum load disturbance and the DC link voltage deviation, the DC gain of the transfer function is much less than the critical DC gain. As a result, the system is stable.

V. SIMULATION RESULTS

The proposed algorithm is implemented on the given case study system described in the previous section. The DC link voltage in normal conditions (base load) is 850 V. AC/DC converter rectifies the conventional grid from 400 V AC to 850 V DC, and the boost chopper increases the output of DRC from 200 V DC to 850 V DC. Three-phase consumers are connected to the system by a three-phase inverter. The inverter changes the DC link voltage to 380 V AC at 60 Hz while the base local demand is

60 kW, and two scenarios regarding increasing and decreasing the load are studied. Table 1 presents the system parameters that are given in APPENDIX A.

A. Without secondary controller

In this case, the load voltage is varied by the load changes if the hybrid system lacks a secondary controller. The maximum acceptable range for load voltage variations is $\pm 5\%$ pu. For small load fluctuations, the system can maintain the AC side load voltage within this range. But, Fig. 10 clearly shows that the load voltage decreases to 0.81 pu between 0.8-1.3s duration when the consumption power increases to up to 30%. As shown, this reduction for the system voltage is not acceptable from an operation system point of view. Also, Fig. 10(b) shows the DC link voltage under load variations. As mentioned in the previous section, the DC link voltage is fixed at 850 V without any changes. Likewise, when the power consumption decreases to 70% of the base load, the load voltage increases to 1.25 pu without any changes in the DC link voltage. Fig. 11 clearly confirms this fact.

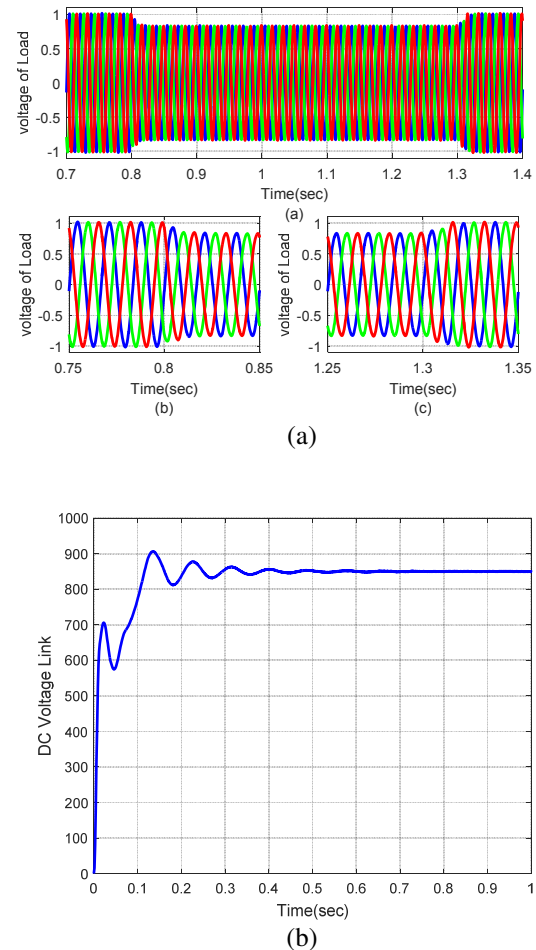


Fig. 10. Load voltage under disturbance without a secondary controller. a) AC side voltage, b) DC link voltage

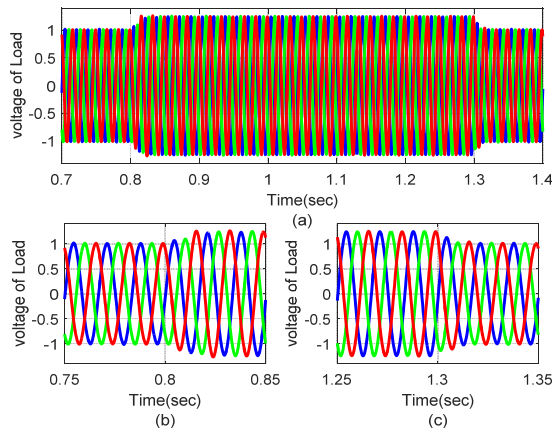
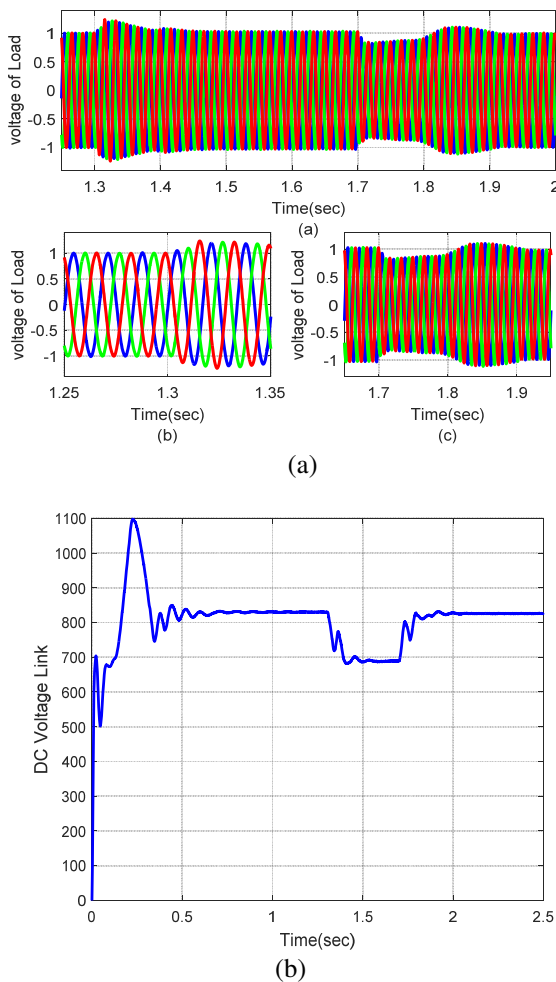


Fig. 11. Load voltage under decreased load demand

B. With secondary controller

In this section, load variations in the presence of a secondary controller are investigated. The results show that the secondary controller influences the power system stability. Fig. 12(a) plots load voltage when the power consumption is decreased down to 70% (42 kW) in 1.3-1.70s time duration.

Fig. 12. Load voltage under disturbance with a secondary controller.
a) AC consumer voltage, b) DC link voltage

Without a secondary controller, the load voltage increases up to 1.25 pu, but the load voltage returns to the initial condition after 20 ms without any deviations when the secondary controller is presented. Returning to the initial situation when there are not any disturbances in the system is one of the main challenges for every controller. Indeed, the controller should be able to return to the initial condition. Fig. 12(a) shows that the load voltage quickly returns to the previous situation after the end of disturbance. The main reason of this change is the variations occurred at the DC link voltage. As shown in Fig. 12(b), the DC link voltage will be changed due to the fluctuations at the set point of two main controllers (grid rectifier and boost chopper) whereas the set point value is determined by the SSC.

The initial value of the DC link voltage is 850 V and it is constant before any disturbances. At 1.3s, the power consumption decreases up to 70% of the initial value and SSC changes the output of the AC/DC converter and boost chopper quickly. In addition, the DC link voltage is decreased to 690 V as shown in Fig. 14 at 1.55 s (25 ms after eliminating the disturbance). Therefore, the three-phase load voltage comes back to the initial value quickly by decreasing the DC link voltage. The variations of the load current are shown in Fig. 13.

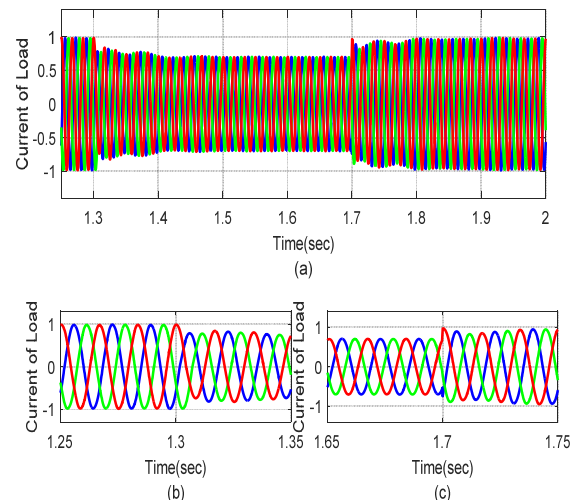


Fig. 13. Load current under the decrease in load demand

In another situation, the power consumption is increased up to 1.3 pu (80 kW) within 1.0-1.5 s. By increasing power consumption, it is expected that the voltage of consumers will decrease. However, the consumer voltage has smooth transient and comes back to the initial value quickly when the secondary controller is used. Fig. 14 shows the load voltage and current, respectively.

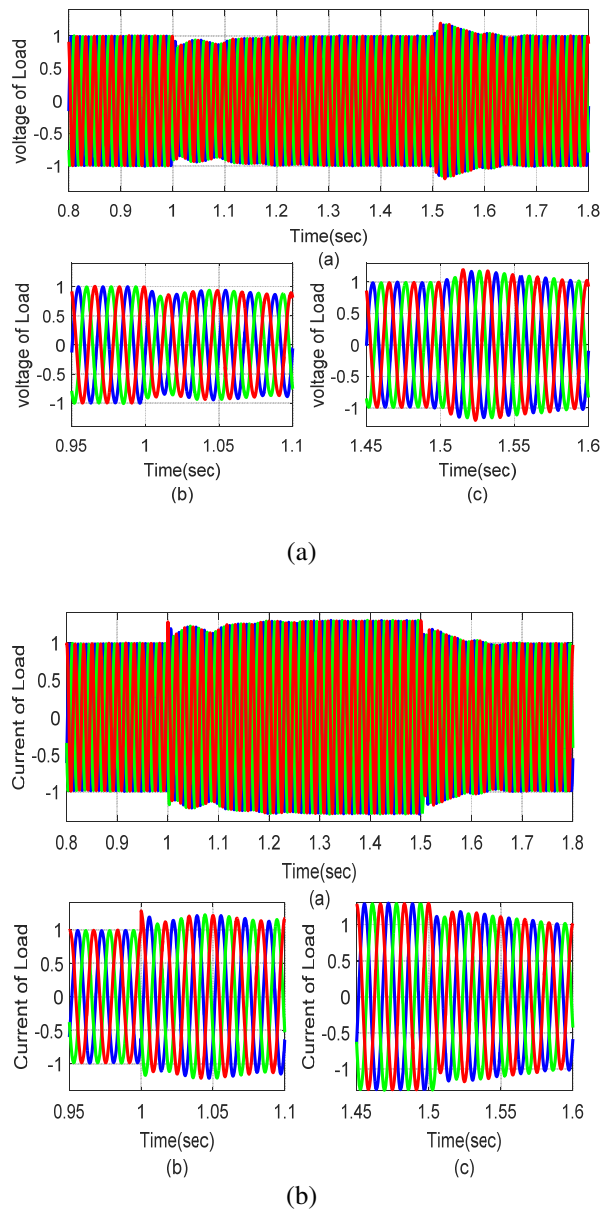


Fig. 14. Load voltage and current under 30% increase in load demand, respectively.

As shown in Fig. 14, the consumer voltage comes back to the initial value in less than 20 ms after disturbance (an increase by 30% power demand). In fact, the DC link set point is changed by the SSC. On the other hand, after the elimination of disturbance, the DC link voltage comes back to the initial values. Hence, the consumer voltage returns to the initial values. Fig. 15 plots the variations of the DC link voltage over time. After disturbance, the DC link voltage is increased from 850 V to 1020 V to supply the load demand without any decreases in load voltage.

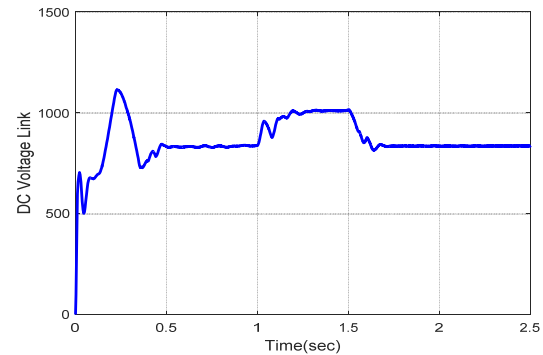


Fig. 15. The DC link voltage when load demand is increased

VI. CONCLUSION

In order to enhance the use of renewable energy resources in electrical systems, an effective control plan must be provided in all operating conditions. In fact, hybrid AC-DC MGs can be expressed as a future ideal electrical MG. In this paper, a DC link is used to connect an electric power producer such as a conventional power system and DGs whose outputs are collected in DRC. Conventional power grids can be converted to DC by an AC/DC converter, and the voltage level of DRC can be changed by a boost chopper. They are connected with DC link and connect a three-phase consumer to the DC link by a three-phase inverter. In current research, a new control algorithm is proposed for damping load variation effects. By setting the set point of controllers, the proposed controller could produce dynamical DC link voltage. Accordingly, the load changing in power system can be controlled widely. The SSC determines the set point of AC/DC converter and boost chopper. The matrices of the system state space are calculated, and the stability analysis is done. All of the system eigenvalues are on the left-hand side of the imaginary axis when a secondary controller is applied. It was shown that the system became unstable without the secondary controller. Also, the system stability was investigated by the root locus diagram. By implementing the proposed controller, it was observed that the load voltage had a small variation in a wide range of load variations. According to the results, the proposed controller is fast, simple, and robust against load disturbances.

APPENDIX. A

SYSTEM PARAMETERS

Table 1. The system parameters

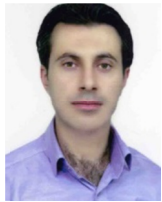
Rectifier parameters	Value	Inverter parameters	Value
K_{p1-d}	7.3	K_{p3-d}	5
K_{p1-q}	7.5	K_{p3-q}	9
K_{i1-d}	43.1	K_{i3-d}	33
K_{i1-q}	42	K_{i3-q}	30
K_{i2}	25.8	R_f	2 m Ω
K_{p2}	0.175	L_f	10 μ H
R_1	0.12 Ω	C_f	350 μ F
L_1	0.04 H	$N_1:N_2$	1
Chopper parameters	Value	ω_0	60 Hz
K	0.765	R_L	1.1 Ω
L_{ch}	2 mH	L_L	0.16 H
C_{dc}	46 μ F	Secondary parameter	Value
R_{ch}	0.02 Ω	M	0.92

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