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Enhancing Renewable Energy Integration with Grid-Forming Converter-Based HVDC Systems: Modelling and Validation

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Abstract: - Pollution free renewable energy sources are key solutions for increasing power demand. Unpredictable nature of power electronic based renewable energy sources impacts negatively on grid voltage and frequency profile. Energy storage is one of the solutions to overcome fluctuating power generation from renewable energy sources. Shorter life span of energy storage makes it costly. Grid forming control is another solution to overcome fluctuating power generation from renewable energy sources. Grid forming converters can regulate voltage and frequency of existing grid by regulating output active and reactive power. Grid forming converter can also form the grid for the remote area where the loads are isolated from utility grid. To regulate output active power grid forming converter also require energy storage when utilized with renewable energy sources. High Voltage Direct Current (HVDC) with one of the converters operating under grid forming mode can supply large isolated load. Renewable energy sources which is operating under grid following mode can also be integrated with High Voltage Direct Current (HVDC) with one of the converters operating under grid forming mode. In this research work, capability of grid forming converter based HVDC in varying load condition has been verified. To understand the effect of integration of renewable energy with grid forming based HVDC, Doubly Fed Induction Generation (DFIG) based wind turbine has been integrated. To validate the capability of grid forming converter based HVDC modelling has been done in Simulink/MATLAB. Results show that Grid forming converter based HVDC system is capable to fulfil the load demand in varying load/generation condition.

Keywords: Grid-Forming, HVDC, Doubly Fed Induction Generator, DFIG, Wind Energy

Introduction

Electrical energy is prime requirement for society. The AC current was invented in 1831 AD by Michael Faraday [1]. The first electric power transmission line in North America operated at 4000 V. It went online on June 3, 1889, with the lines between the generating station at Willamette Falls in Oregon City, Oregon, and Chapman Square in downtown Portland, Oregon stretching about 13 miles [2]. Since than efforts have been made to transfer AC current at higher voltage to reduce the losses and achieve long distance transmission. Maximum AC transmission voltage achieved is 765 kilovolts (kV) in 1968 by American Electrical Power Company in US. There has been no further increase in transmission voltage used for commercial system [3]. The first High Voltage Direct Current Transmission was developed in 1920 [4]. The first commercial HVDC link was built in 1954, carried power between the mainland of Sweden and the island of Gotland [5]. There are number of Sweden differences between HVAC & HVDC Transmission. Some of them are as follows.

- Line losses are significantly lower for DC
- ➢ For an example; for 800 kV DC Link of 2000 Km, line losses are 5
- ➢ For a same length 765 kV AC Link, line losses are 10
- For same amount of power transmission DC Link cost is lower than AC Link
- Control of power is easy in DC Link compared to AC Link
- For a short length DC Link is expensive due to the power electronics required in DC Link.

High Voltage DC Transmission (HVDC)

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HVDC is plays its important role in this smart grid era. HVDC system is capable to connect two different AC system with frequency and phase conversion [6]. With compared to AC system DC system has low losses due to the absence of AC resistance in DC system. DC system does not have reactive power and hence there is no issues of length of transmission line. Due to above mentioned reasons HVDC system is preferable for long distance transmission [7]. HVDC can transmit more power for a given transmission corridor size than AC. Where space is constrained, this may mean that, in future, HVAC lines may be replaced by HVDC.

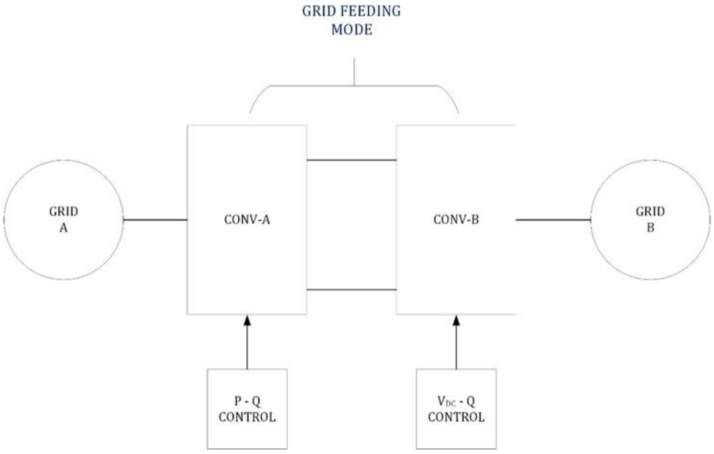

Figure 1 Simple structure of HVDC

Simple structure of HVDC is shown in figure.1. It consists of back-to-back converters. It is capable to flow the power in both the direction. As shown in figure one of the controllers is working under V_{DC}−Q control whereas another converter work under V-F control. V-F controller decide the amount of active/reactive power of CONV-A along with its direction (Injection/Absorption). As the CONV-A inject/absorb the power into/from grid it will change the energy level in DC-Link which can be observed from the voltage of DC-Link. By maintaining DC-Link voltage V_{DC}−Q controller makes CONV-B to inject/absorb same amount of which has been injected/absorbed by CONV-A.

A. Converter for HVDC

The High Voltage Direct Current (HVDC) system necessitates the integration of two bidirectional converters connected back-to-back, facilitating power flow bidirectionally. A fundamental choice for such a bidirectional converter is the Two-Level Converter [8]. Comprising six semiconductor-based switches, the Two-Level Converter, when appropriately switched, generates three-phase output voltages with a 120-degree phase shift. Alternatively, the Three Level Diode Clamped Multilevel Converter, [9], stands as another topology option. Renowned for offering reduced voltage harmonics in its output compared to the Two-Level Converter, the Three Level Diode Clamped Multilevel Converter additionally alleviates voltage stress on the switches by half. Beyond these, various other converter topologies find application in HVDC systems, including the Three Level Active NPC, Modular Multilevel Converter (MMC), and Cascaded Two Level Converter (CTL) [8-10], respectively. Each topology presents distinct advantages and trade-offs, contributing to the diversity of solutions available in the realm of High Voltage Direct Current systems.

B. Control of HVDC

To comprehend the power sharing attributes among inverters and generators, it is important to audit the two fundamental control methods of inverter 1) grid following control mode 2) grid forming control mode. Figure 2 shows grid following control mode whereas figure 3 shows grid forming control mode. Former control mode makes inverter to act like constant current source and latter control makes inverter to act like constant voltage source. Grid forming control mode is not reasonable for paralleling with other voltage sources, and grid following control mode is regularly phase locked loop (PLL) driven, and hence require another voltage source to be operative. [11]

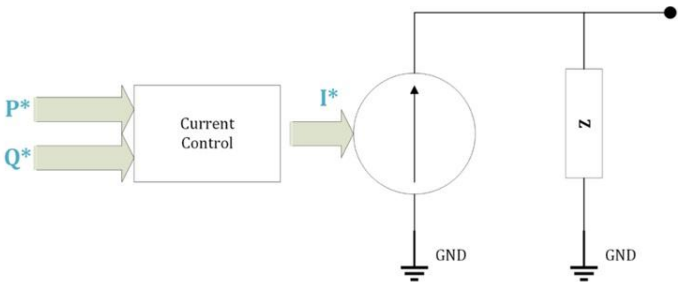

Figure 2 Grid Following Control

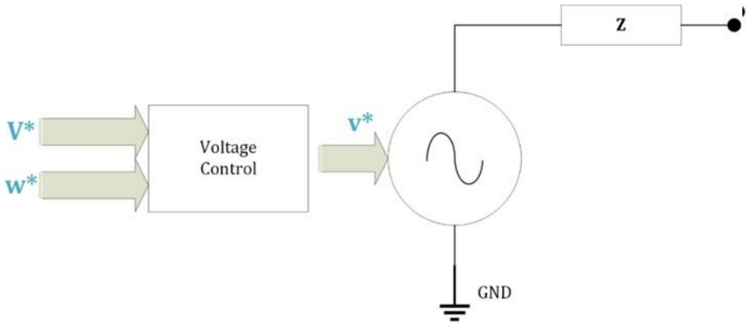

Figure 3 Grid Forming Control

1) Grid Following Control:

The control logic for grid following is shown in Figure 4. Grid following control logic can be divided in three parts.

- Power Controller
- Current Controller
- PWM Generator

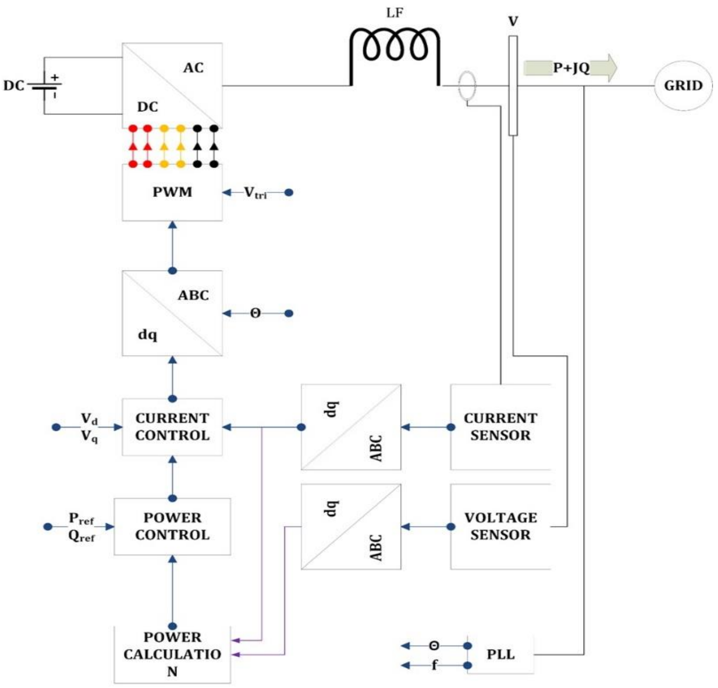

Figure 4 Grid Following Control

As shown in Figure 4, Power controller serves as an outer loop for the grid following converter. Based on the given active power/reactive power references power controller generates current reference signal in synchronously rotating reference frame. By assuming the voltage alignment with direct axis, power controller generates in phase component I_d (direct axis current) from the given active power reference and orthogonal component I_q (quadrature axis current) from the given reactive power reference. In synchronously rotating reference frame power can be expressed mathematically as follow

$$P = \frac{3}{2}\left(V_d I_d + V_q I_q\right)$$

$$Q = \frac{3}{2}\left(V_q I_d - V_d I_q\right)$$

In these P, Q, I_d, I_q, V_d, V_q represents, active power, reactive power, direct axis current, quadrature axis current, direct axis voltage and quadrature axis voltage respectively. For the independent control of active and reactive power, V_d should be kept to 1 P.U. and V_q should be kept at 0 P.U. I_d and I_q should be decoupled. From this power equation get modified and can be given as follow.

$$\begin{aligned} P &= \frac{3}{2}(V_d I_d) \\ Q &= \frac{3}{2}(-V_d I_q) \end{aligned}$$

If the grid voltages are balanced positive sequence set of voltages, then by aligning voltage vector with d-axis by the help of sophisticated Phase Locked Loop V_d becomes 1. Any error in PLL can generate V_q and independent control of active and reactive power would be compromised. Hence PLL should be designed in such a manner that it only extracts angle from positive sequence balanced set of voltage. For that appropriate filters can be used to nullify any distortion in voltage signals before feeding it to PLL. To design a current controller following equations has been utilized.

$$\overline{V}_d^{*} = \overline{V}_d^{\mathrm{PCC}} - i_d R_f - L_f \frac{di_d}{dt} + j\omega L_f i_q$$

$$\overline{V}_q^{*} = \overline{V}_q^{\mathrm{PCC}} - i_q R_f - L_f \frac{di_q}{dt} - j\omega L_f i_d$$

$\overline{V}_d^{*}$ is the Reference Direct Axis Voltage, and $\overline{V}_q^{*}$ is the Reference Quadrature Axis Voltage. $\overline{V}_d^{\mathrm{PCC}}$ represents the Direct Axis Voltage at the Point of Common Coupling (PCC), and $\overline{V}_q^{\mathrm{PCC}}$ is the Quadrature Axis Voltage at PCC. I_d and I_q denote the Direct Axis Current and Quadrature Axis Current, respectively. L_f is the Filter Inductance, R_f is the Filter Resistance, and ω stands for Angular Frequency. In equations coupling effect of I_d and I_q can be observed. $j\omega L_f I_q$ and $j\omega L_f I_d$ are the decoupling term which makes I_d and I_q independent from each other [12]. The control logic derived from equations can be observed in figure 5.

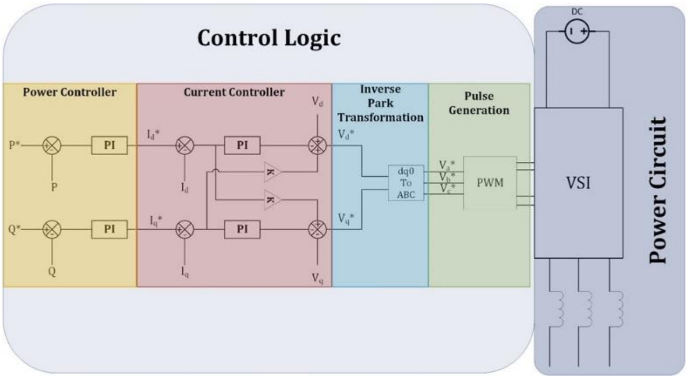

Figure 5 Control Logic: Grid Following Converter

Voltage references from current controller are in synchronously rotating reference frame which then converted to ABC reference frame by using inverse park transformation.

$$\begin{bmatrix} \overline{V}_A^* \\ \overline{V}_B^* \\ \overline{V}_C^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \cos(\theta) & 1 \\ \sin(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & 1 \\ \sin(\theta + \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} \overline{V}_d^* \\ \overline{V}_q^* \\ \overline{V}_0^* \end{bmatrix}$$

Three reference signals $\overline{V}_A^*$, $\overline{V}_B^*$ and $\overline{V}_C^*$ are then utilized to synthesize sinusoidally modulated gate pulses. For the Sine Pulse Width Modulation (SPWM), sinusoidal references $\overline{V}_A^*$, $\overline{V}_B^*$ and $\overline{V}_C^*$ are compared with a triangular carrier wave.

2) Grid Forming Mode:

In grid forming mode power controller get replaced with voltage controller. This voltage controller ensures the injected voltage to be balanced positive sequence set of voltage. [13] Grid-connected inverter generates constant magnitude and frequency of three-phase voltage under grid-forming mode control. This mode works when grid is not available, thus it supplies its own local load from the energy source connected to DC side. Figure 6 shows the complete grid-forming mode control of grid-connected inverter. It consists of double-loop control of current and voltage control section, voltage reference section, and measurement section. Voltage reference is internal three-phase signal through dq transformation and PLL. This scheme generates three phase voltage V_{abc}, which follows the voltage reference.

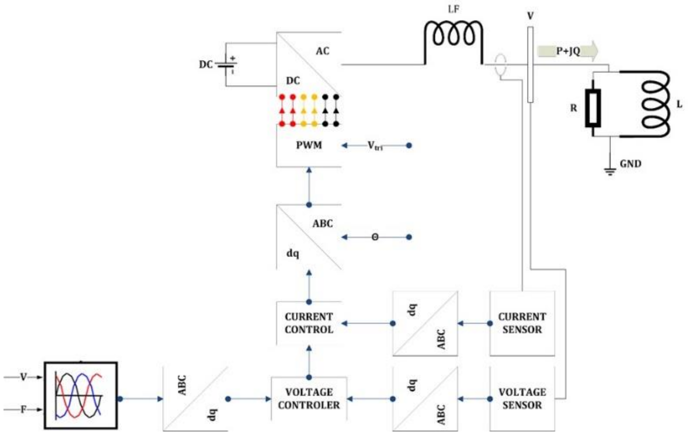

Figure 6 Control Logic: Grid Forming Converter

Phase-locked loop (PLL) is a popular method used to synchronize power electronic converter with grid. In such kind of applications, PLL's role is essential to provide accurate and fast detection of utility phase angle for generating reference signal of grid-connected inverter. The common method to realize PLL on three-phase system is by using synchronous frame PLL. Figure 7 shows the block diagram of synchronous frame PLL. Instantaneous phase angle θ is detected by synchronizing the reference frame with the vector of three-phase voltage (V_a, V_b and V_c). To be locked to the phase angle of utility voltage vector, the Proportional–Integral (PI) controller drives V_q to be zero, as given by the reference V_q^*, which gives the angular speed quantities. Phase angle θ is simply obtained by integrating the angular speed.

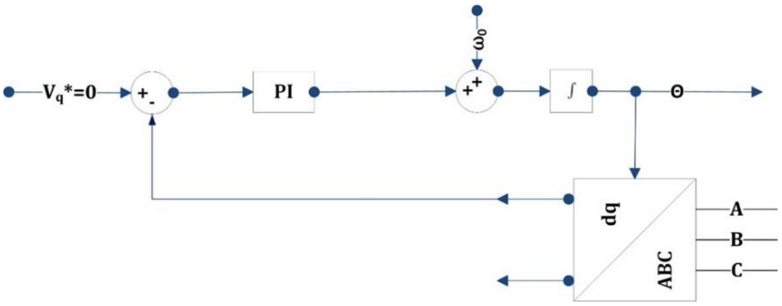

Figure 7 Phase Locked Loop

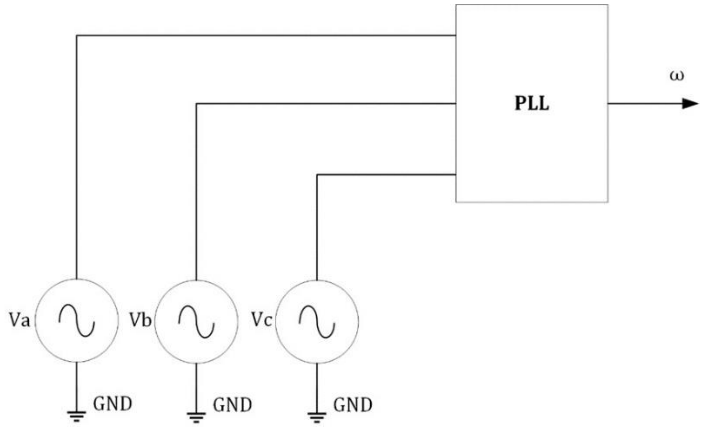

Figure 8 Voltage References

As there is no grid voltage hence voltage parameter like frequency and sequence should be provided internally as shown in Figure 8. In Figure 8 value of V_a, V_b and V_c can be given as follows. To ensure that injected voltage remain balance and in positive sequence voltage controller maintain value of V_d to 1 and value of V_q to zero. [14-15]

$$V_a = m\sin(2\pi f)$$
$$V_b = m\sin(2\pi f + \frac{2\pi}{3})$$
$$V_c = m\sin(2\pi f - \frac{2\pi}{3})$$

Where f is required frequency 50 Hz or 60 Hz.

Angular frequency ω extracted from PLL in Figure.8, further utilized for the Inverse Park transformation shown in Figure.7, which ensure injected three phase voltage remain in phase/have same angular frequency as per provided internal reference V_a, V_b and V_c. Current reference in grid forming mode is generated in different manner. To ensure that injected voltage remain in balance and in positive sequence, voltage controller maintain value of V_d to 1 and value of V_q to zero as shown in Figure 9. For the fulfillment of active/reactive power demand of load while maintaining V_q to zero, the voltage controller generates direct current reference I_d^* and I_q^*. Reference current I_d^* and I_q^* then again converted to reference voltages V_d^* and V_q^* with the help of current controller explained in previous section.

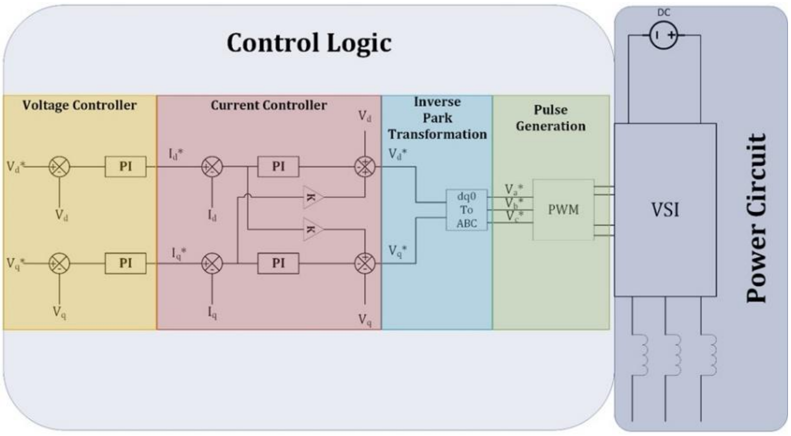

Figure 9 Control Logic Grid Forming Converter

Comparison of grid following converter and grid forming converter is shown in below Table 1.

Table 1 Comparison Grid Following - Grid Forming

Grid Following Control	Grid Forming Control
• Controls current and phase angle	• Controls voltage magnitude and frequency
• Control of active & reactive power as well as fault currents	• Instantaneously balances loads without coordination controls
• Cannot operate standalone	• Can operate standalone
• Cannot achieve 100% penetration	• Can achieve 100% penetration

High Voltage Direct Current System in Grid Forming Mode

As shown in Figure 10 grid forming mode has been utilized in one of the converters in HVDC. To feed the isolated load connected to Converter-1, grid forming mode can be implemented. In grid forming mode Converter-1 synthesize the grid voltage.

In this Converter-2 operates in grid following mode. To fulfill the load demand Converter-1 provides the required power while regulating load voltage and frequency. Converter-2 supports the Converter-1 by injecting same active power into the DC-Link. Here it should be noted that reactive demand of load is solely fulfill by Converter-1 only.

If any distributed generators (DG) are connected to the load side than according to Power Generation and load demand power flow within HVDC system get changed. This can be understood by considering three different modes of operation.

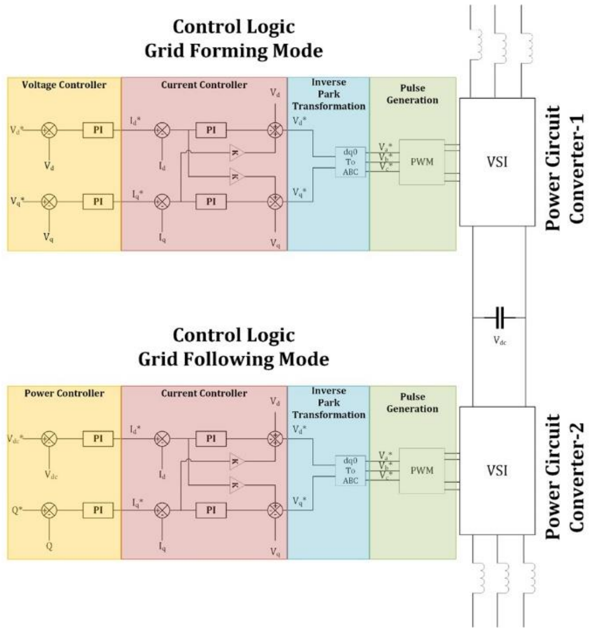

Figure 10 Control Logic HVDC

Mode-1: No Power Generation from Distributed Generation (P_{DG}= 0)

In this mode load demand get fulfilled by converter-1. Converter-2 provide the active power required by the load. In this mode Converter-1 act as an inverter and Converter-2 act as rectifier. Converter-2 also fulfill the DC-Link losses and losses related to Converter-1. This mode of operation is shown in Figure 11.

Mode-2: Power Generation from Distributed Generation lesser than load demand ($P_{DG} < P_{Load}$)

In this mode load demand get fulfilled by converter-1 and distributed generation. Converter-2 provide the active power equal to P_{Load} - P_{DG}. In this mode, Converter-1 act as an inverter and Converter-2 act as rectifier. Converter-2 also fulfills the DC-Link losses and losses related to Converter-1. Reactive power demand of load is fulfilled by converter-1 along with DG (if DG has capability to generate VAR). This mode of operation is shown in Figure 12.

Mode 3: Power Generation from Distributed Generation greater than load demand ($P_{DG} > P_{Load}$)

In this mode load demand get fulfilled by distributed load generation. As the distributed generation is greater than load demand remaining power get transferred toward grid side. In this mode Converter-1 act as rectifier and Converter-2 act as an inverter. Reactive power demand of load is fulfilled by converter-1 along with DG (if DG has capability to generate VAR). This mode of operation is shown in Figure 13.

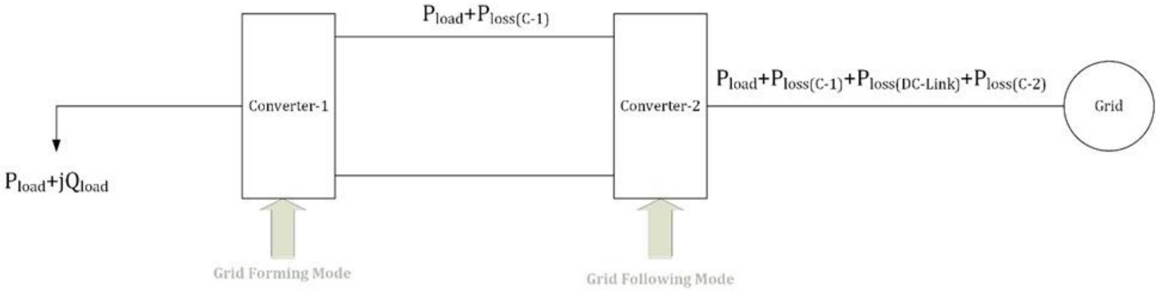

Figure 11 Mode-1

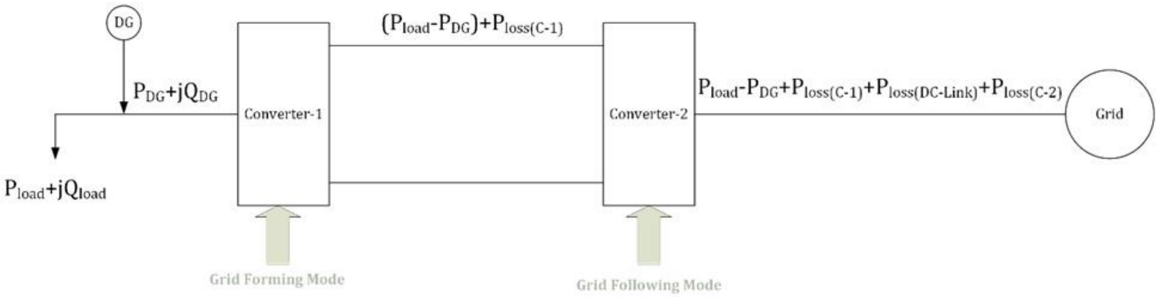

Figure 12 Mode-2

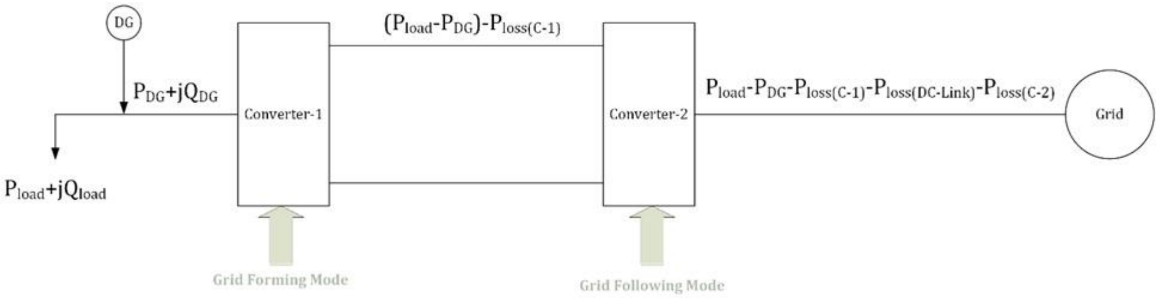

Figure 13 Mode-3

Result & Discussion

Grid Forming Converter is able to regulate its voltage and frequency as per the load requirement. Integration of Grid Forming Converter with HVDC provide flexible power flow between grid connected at one end and loads connected at another end. Capability of GFI to regulate voltage and frequency in varying load environment has been analyzed in this section.

Grid Forming Inverter (GFI) has been integrated with HVDC to feed the isolated load connected at GFI side. Normally HVDC System have two bidirectional converters connected to AC Grid. To feed isolated load one of the HVDC Converter is controlled by Grid Forming Control strategy. Parameter of considered system is shown in Table 2.

Table 2 System Parameters

PARAMETERS	VALUE
POWER GRID	

• Grid Voltage (Line-Line)	230 kV
• Frequency	60 Hz
GRID SIDE CONVERTER	
• Power Rating	200 MVA
• Voltage (Line-Line)	100 kV
• Frequency	60 Hz
• DC-Link Voltage	200 kV
LOAD SIDE CONVERTER	
• Power Rating	200 MVA
• Voltage (Line-Line)	100 kV
• Frequency	60 Hz
• DC-Link Voltage	200 kV
LOAD	
• Voltage (Line-Line)	100 kV
• Frequency	60 Hz
• Maximum Loading	200 MVA

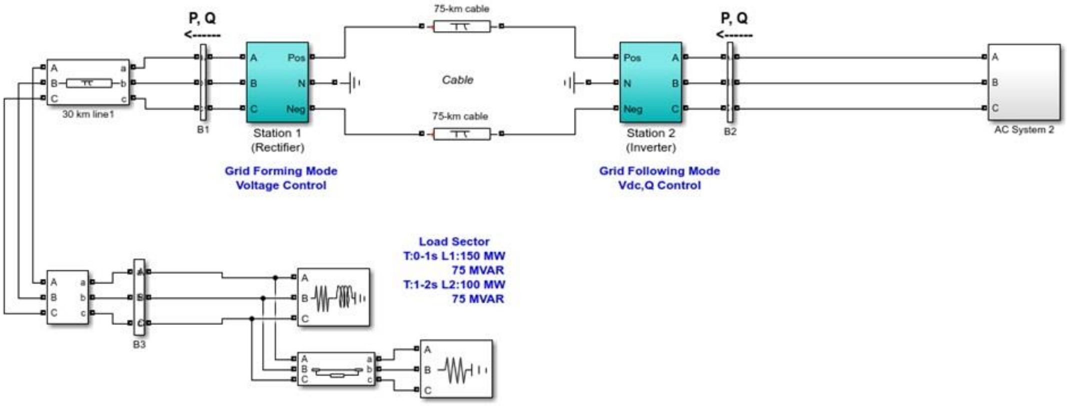

Figure 14 Simulink Diagram of GFI based HVDC

Figure 14 shows Simulink diagram of GFI based HVDC. There are two converters in HVDC in which Station 1 is connected to load and operating under Grid Forming Mode. Station 2 is connected to grid and operating under grid following mode. GFI based HVDC in this section has been simulated with varying load demand. The load demand has been summarized in Table 3.

Table 3 Load Change

Time	Loading
0 – 1s	0.75 P.U. (0.9 PF Lagging)
1 – 2s	0.5 P.U. (0.8 PF Lagging)

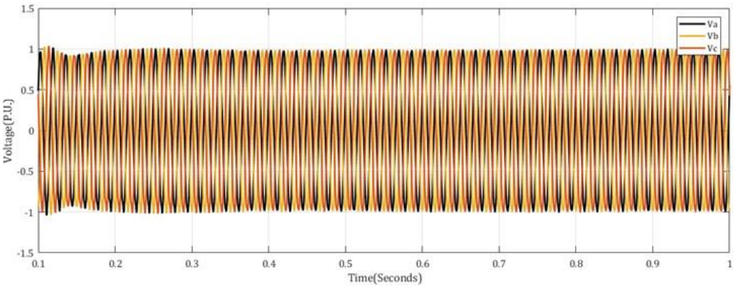

Figure 15 Injected Voltage of Load Side Converter

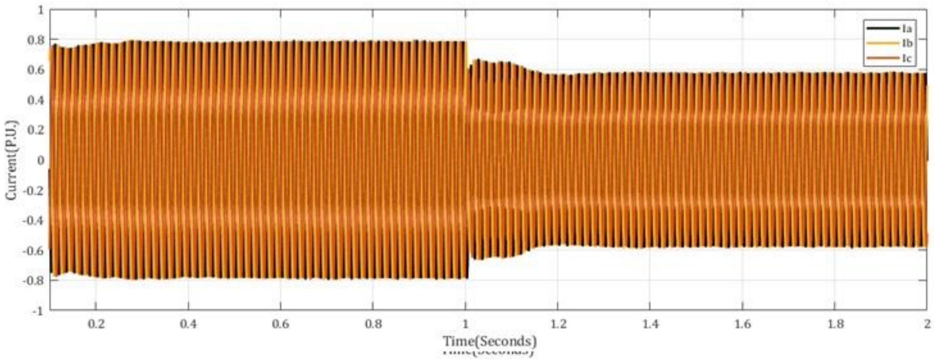

Figure 16 Injected Current of Load Side Converter

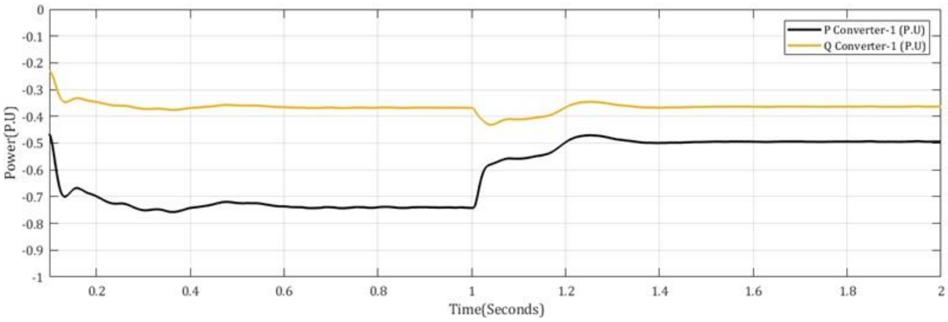

Figure 17 Injected Power of Load Side Converter

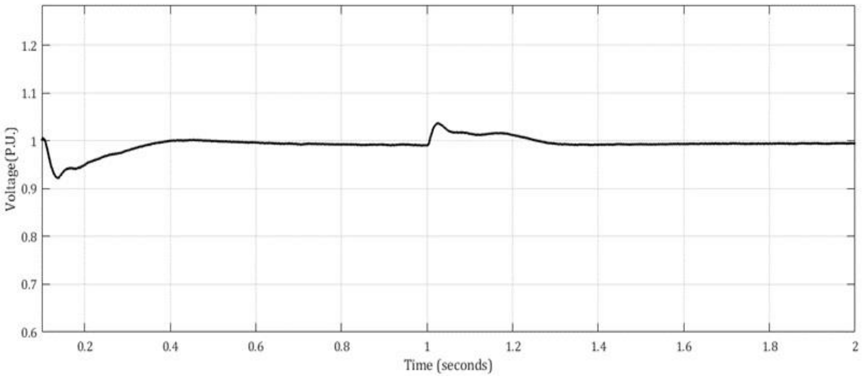

Figure 18 DC-Link Voltage

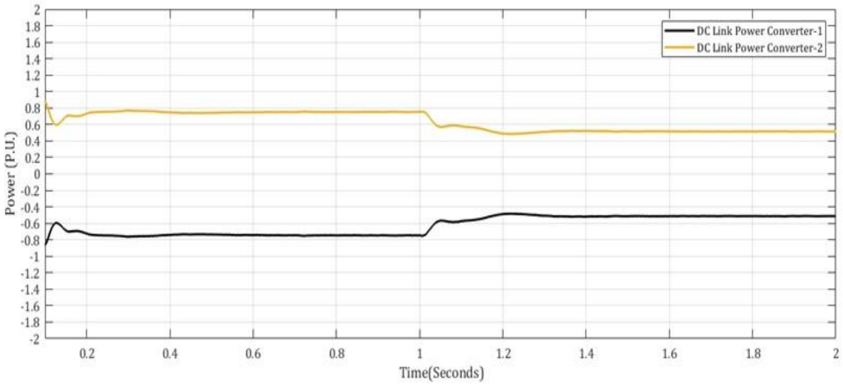

Figure 19 DC-Link Power

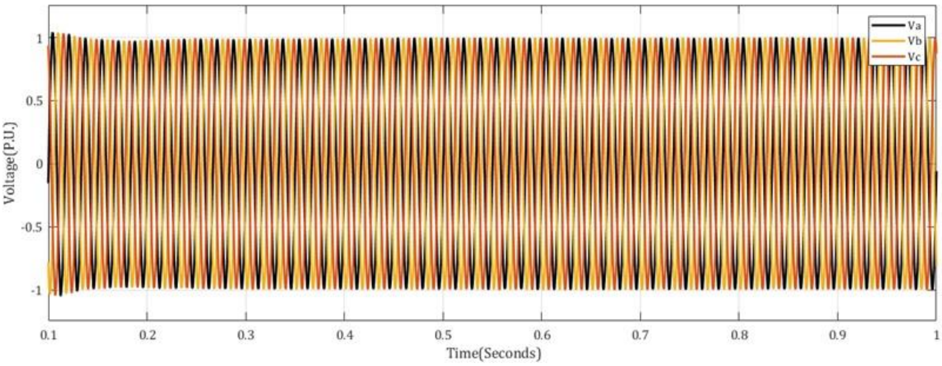

Figure 20 Injected Voltage of Grid Side Converter

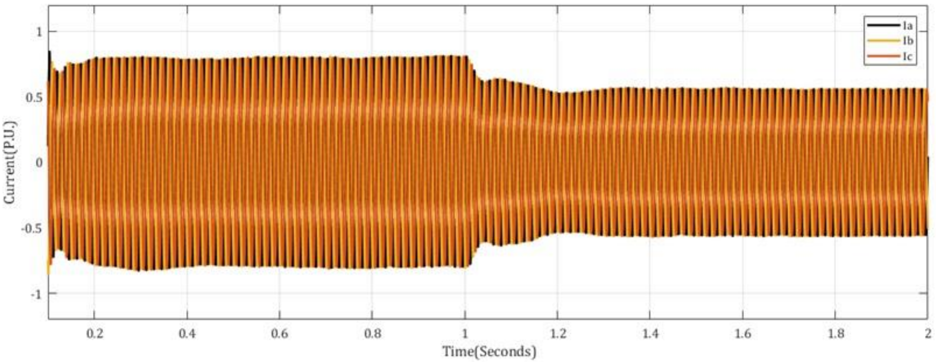

Figure 21 Injected Current of Grid Side Converter

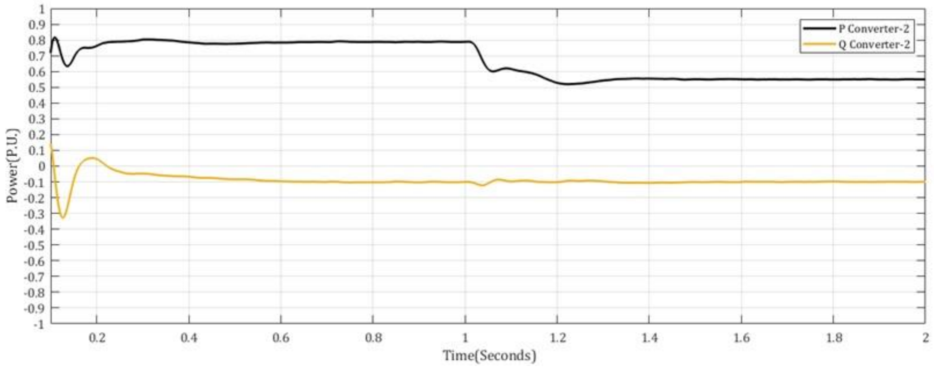

Figure 22 Injected Power of Grid Side Converter

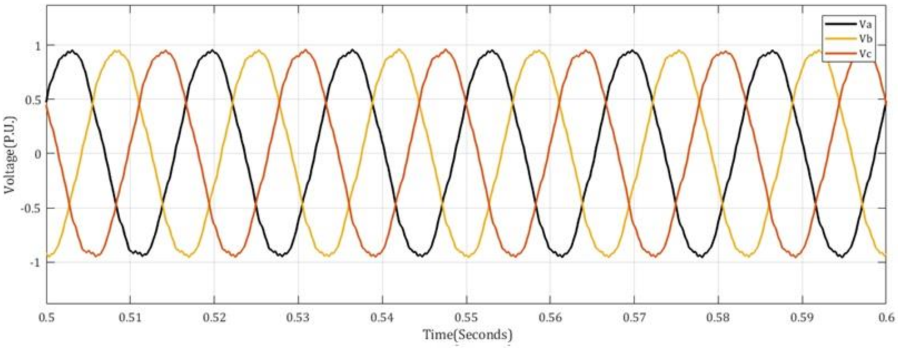

Figure 23 Load Voltage

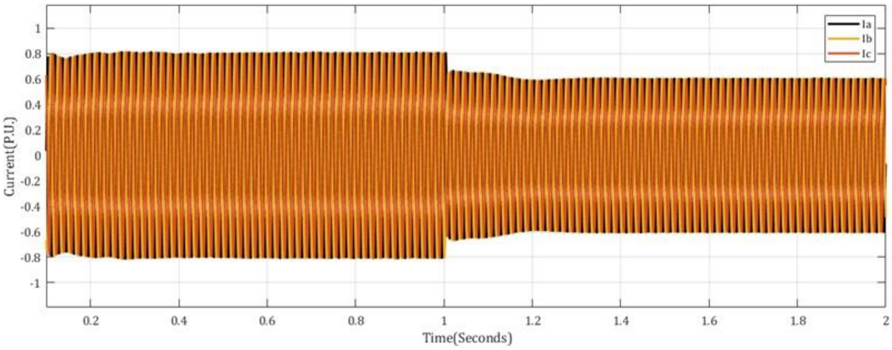

Figure 24 Load Current

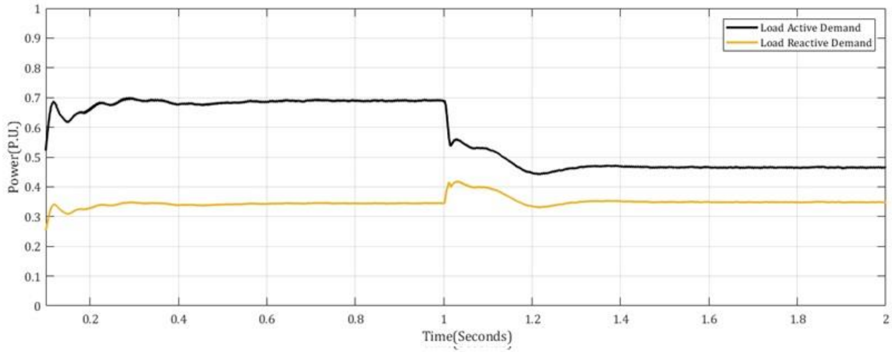

Figure 25 Load Power

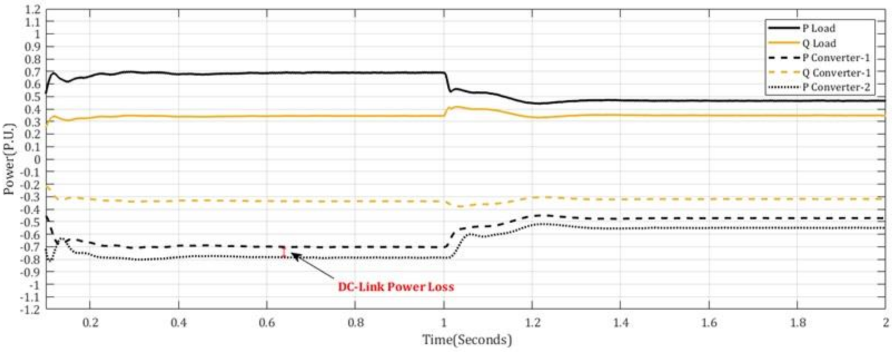

Figure 26 Power Analysis of Simulated System

Figure 15 to Figure 26 shows the results of GFI based HVDC system in dynamic loading condition. Figure 15 to Figure 17 shows the result of GFI control-based Converter-1. Figure 15 shows the voltage at PCC which remains constant at 1 P.U. due to outer voltage control loop of GFI control structure. Figure 16 shows the sinusoidal current injected at PCC. Figure 17 shows the power injected by HVDC system at load side.

As shown in Figure 25 load demand at 0 to 1 second is 0.75 P.U., which has been provided by converter-1 as shown in Figure 17. It is also observed that DC Link power loss is approximately 0.08 P.U. as converter-2 is injecting 0.83 P.U. into the DC-Link. Active power demand of load is reduced to 0.5 P.U. after 1 second, which also reduce the power injection of converter-1. Reactive power demand of the load is constant equal to 0.37 P.U. which is solely provided by converter-1.

Conclusion

Pollution free renewable energy sources are the solution for increasing load demand. Grid forming converter provide support to machine-based generation in voltage and frequency regulation. Grid forming converter is also useful to fulfil the load demand of isolated consumers. Grid forming based HVDC can provide large amount of power to remote consumer. It can also handle the renewable energy generation which is having fluctuating nature and require energy storage if connected directly to the load. HVDC is able to provide bi-directional power flow and hence energy storage can be eliminated. In grid forming mode HVDC Converter ensure rated frequency and rated voltage at PCC.

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