Control Topology for Emulating the Behavior of Synchronous Machines in Voltage Source Converters

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***Abstract*—This paper presents a control strategy based on the VSC emulating the behavior of synchronous machines. VSCs are the preferred electronic interfacing devices used for interfacing the distributed generators units or renewable generation units with the ac system in this paper. The regulation of the dc-link voltage helps in integration of these VSCs in the existing system in the presence of conventional synchronous machines. Two loops are designed each, to emulate the mechanical behavior of an SM which offers synchronization power to eliminate the need for a phase- locked- loop after initial converter synchronization, and damping power dynamics to damp power oscillations. This presents frequency dynamics similar to SMs, thus it introduces some inertia to the grid. Two different topologies for the dc-link voltage control are presented- direct dc-link voltage control and virtual torque control. These topologies are simulated using and the results of both the topologies are shown.**

Index Terms— **Voltage Source Converters (VSC), Synchronous Machines (SM), Synchronous Generator (SG), dc-link voltage, Virtual torque, Virtual inertia**.

I. INTRODUCTION

With the increase in demand of power and to increase the quality of power, the integration of renewable generation sources in to existing grid has seen to a shift in the paradigm of power system from centralized power generation system to distributed generation. In order to integrate the renewable energy sources into the grid, power electronic devices are used as interfacing units between the distributed generation units and the grids. Thus controlling the power electronics interfacing units is vital part of improving the reliability of the system. However, as an increasing percentage of the available system power generation is being provided by non-synchronous generators, the resulting loss of inertia in the system can lead to degraded performance, including grid-frequency instability [3].

Conventional synchronous generators (SGs) comprise rotating inertia due to their rotating parts. These generators are capable of injecting the kinetic potential energy preserved in their rotating parts to the power grid in the case of disturbances or sudden changes. Therefore, the system is robust against instability. But with the increase in the integration of the DG units the most challenging issue with the electronic interfaced units is to synchronize the interfacing unit i.e., VSC with the grid and then to keep it in step with the grid even when disturbances or changes happen. A power system with a big portion of electronic-based DGs is prone to instability due to the lack of adequate balancing energy injection within the proper time interval. The solution can be found in the control scheme of electronic-based DGs.

The conventional voltage - oriented vector control [3] and direct-power control [4] of the VSCs include current vector control and direct power control with phase locked-loop (PLL) into transform the *dq* to *abc* components. However, these methods does not include direct control the frequency and the load angle.

To overcome the problem of inertia reduction, VSCs are proposed as virtual synchronous machines for power system frequency stabilization [6]. In [7], the emulation of mechanical behavior of synchronous generator in inverters by considering an ideal dc-link was proposed. In [8]–[10], virtual inertia is emulated in VSCs interfacing wind turbines and HVDC systems; however, the embedded inertia does not emulate the behavior of an SG. This shows the necessity for improved VSC control methods to emulate the dynamic behavior of SGs. To improve dc-link voltage stability, fast response short-term energy storage can be installed in distributed generation (DG) units [9]. Instabilities due to dc-link dynamics are one of major sources of instabilities in VSCs [19]. Most of previous works on virtual SGs and/or self-synchronization of VSCs consider the dc link as an ideal battery with infinite energy [4]–[7], [11].

II. OBJECTIVES

1. A control topology that eases the integration of VSCs into the grid with existing synchronous machines. Thus the dc-link voltage should be adjusted to emulate the behavior of SM.

2. The stored energy in the dc-link should be used for frequency regulation during contingencies just like SM. For this purpose it introduces inertia in the frequency.
3. SMs operate in both motoring and generating mode, this topology should be feasible for oth rectifying and inverting mode without reconfiguration.
4. As PLL dynamics effect the system there is a need for elimination of PLL after initial synchronization.
5. Similar to SMs it is capable of maintaining synchronism during and subsequent to faults. Hence offers fault-ride-through-capability.

The paper is organized as follows. Section 2 shows the proposed control topologies and section 3 shows the simulation results.

III PROPOSED TOPOLOGY

The proposed topologies offer direct control of dc-link voltage, frequency and the load angle with the following stipulations in effect.

1. The VSCs are considered to be lossless, thus equating the input ac power to the output dc power.
2. The reactive power does not correspond with the real power exchange on the converter dc-side.
3. A pure inductor without capacitor is used as output filter in VSC.

4. During contingencies an energy storage system can be installed at the dc-link for transfer of power from the energy storage device to the grid.

a) Synchronous Machine Model

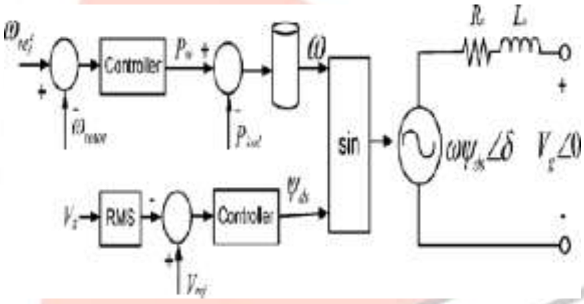


Fig.1. SM principal operation and control concept.

In this paper, the model of a round rotor synchronous motor without damping windings is considered. In fact, the effect of damping and synchronizing powers can be emulated by the control functions in the VSC without physical damping components as in conventional SMs.

The back-EMF voltage amplitude is given by

$$E = \omega\psi_{\mathrm{ds}}. \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \quad 1$$

Where ω is the rotor frequency.

ψ_{ds} is the d-axis flux component.

The virtual electrical torque and reactive power in this case are governed by the following equations:

$$T = \frac{P_{vsc}}{\omega} = \frac{E}{R_s^2 + (L_s\omega)^2}\left(L_s V_g \sin\delta + \frac{R_s(E - V_g\cos\delta)}{\omega}\right) \qquad \text{\_\_\_\_\_\_} \quad 2$$

$$Q = \frac{E}{R_s^2 + (L_s\omega)^2}\left(R_s V_g \sin\delta + (L_s\omega)(E - V_g\cos\delta)\right) \qquad \text{\_\_\_\_\_\_} \quad 3$$

Where δ is the load angle, i.e., angle displacement between the back-EMF and grid voltage, and P_{VSC} is the VSC's power. Assuming an inductive stator winding, the injected real power is mainly regulated by the load angle whereas reactive power is regulated by VSC voltage amplitude. In SGs, the reference power is determined by the governor such that the rated frequency is preserved and the output power or, equivalently, the load power finally becomes equal to the reference power.

(b) Control Strategy

Frequency Control Loop

Here, the proposed topologies for frequency control are presented. For the frequency control, two variants are proposed—namely, virtual torque control and direct dc-link voltage control as depicted in Fig. 2. To generate a three-phase sinusoidal voltage in the polar system, its amplitude, frequency, and angle are required.

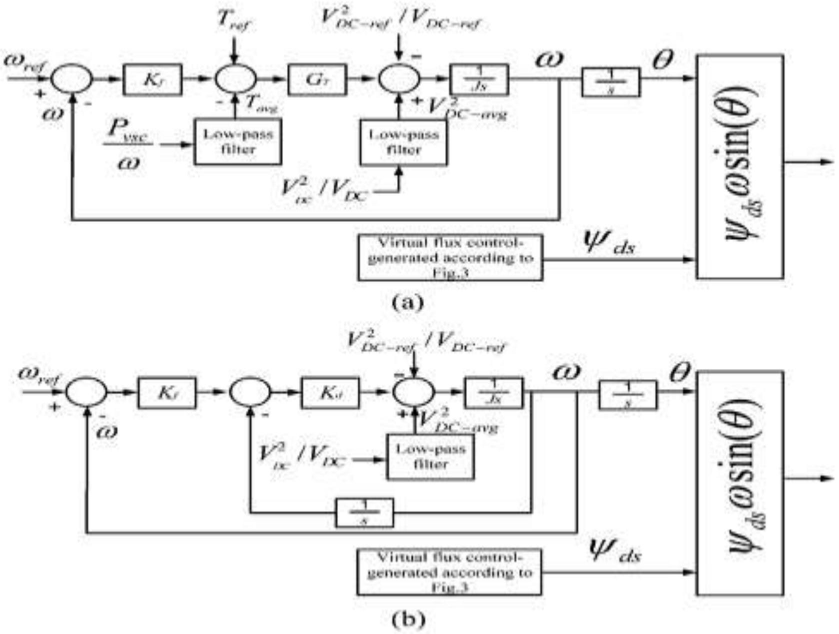


Fig.2. Proposed control topologies for frequency and dc-link voltage regulation. (a) Virtual torque control. (b) Direct dc-link voltage control.

The voltage generation principle in a synchronous-VSC is similar to back-EMF generation in SGs shown in Fig. 1. The back-EMF amplitude is given by , thus the -axis flux and frequency are necessary. Toward this, two separate channels are adopted to independently regulate VSC's frequency and virtual flux, as shown in Fig. 2. The first loop is the frequency control loop shown in Fig. 2, which emulates the mechanical behavior of an SG with proper control of the dc-link voltage and frequency such that grid views the capacitor as a virtual rotor. The angle of the generated sine wave is easily obtained by integrating the frequency. The goal of the second channel, shown in Fig. 3, is to mimic the electrical behavior of SGs by appropriate adjustment of the virtual flux.

An alternative to the virtual torque control topology shown in Fig. 2(a) is the direct dc-link voltage control in which the extra torque regulation loop is removed. In this case, instead of indirect dc-link voltage adjustment via power regulation, the dc-link voltage square, as an index of power, is controlled. This structure is more compact, where all requirements are augmented in one general strategy.

Accordingly, in islanded mode, the dc-link voltage is variable, and, in inverting mode, an increment in the real power increases the load angle and consequently the dc-link voltage. As the scope of this paper is focused on the grid connected mode, the controller operation in islanded conditions is an open question for future studies.

Virtual Flux Control Loop

Similar to an SM, two strategies can be defined in which the voltage is controlled to: 1) generate a pre-specific amount of reactive power and 2) achieve voltage regulation at a specific load-power. These two strategies are shown in Fig. 3.

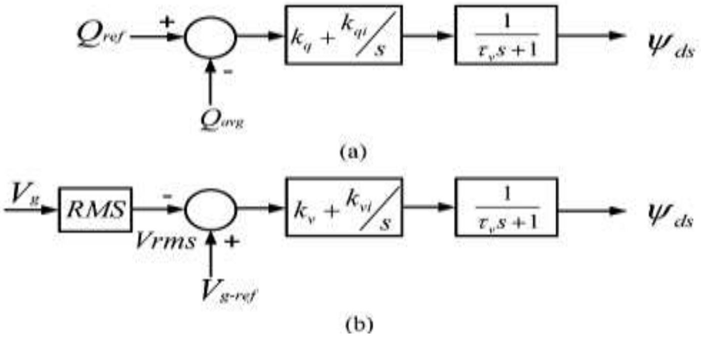


Fig.3. Proposed control topologies for the virtual flux regulation. (a) Constant reactive power operation. (b) Constant voltage operation.

Strategy 1:

Reactive Power Regulation: Usually, the preset value of the VSC input reactive power is set to zero. However, similar to SMs, the synchronous VSC can either absorb (under-excitation) or inject (over-excitation) reactive power to support the grid in various situations. This significantly can enhance voltage stability especially when the grid falls short to provide enough reactive power for some local loads. A PI controller tunes the virtual rotor excitation voltage such that the required reactive power is achieved. The excitation dc voltage is transformed to a virtual air-gap flux through a low-pass filter emulating the flux decay behavior of a real SM caused by the excitation RL circuit.

Strategy 2:

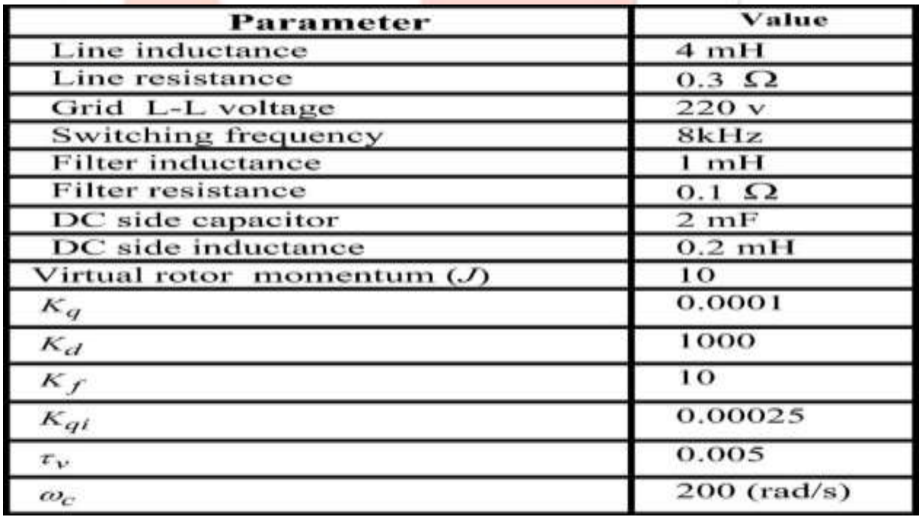
Voltage Regulation: In weak grids where the connecting impedance between converter and grid is high, voltage regulation and stability may be deteriorated, thus, in this case, voltage regulation is of high interest to keep the voltage at the point of common coupling (PCC) at a certain value. The controller specifies the corresponding excitation voltage set-point to regulate the PCC voltage to the reference value.

III. SIMULATION RESULTS

This section presents detailed simulation results of the pro-posed control system. The simulated system is shown in Fig. 7. Simulation studies are carried out in the MATLAB/SIMULINK environment. Different conditions in both generative and rectification modes are considered to show effectiveness and generality of the controller in all cases. The system is simulated under various scenarios of VSC operating conditions. Three scenarios that are taken into account are:

1. Load / generation power change.
2. DC-link voltage reference change
3. Grid voltage change in both rectifying and inverting modes.

TABLE I
SIMULATED SYSTEM PARAMETERS (SI UNITS)



Parameter	Value
Line inductance	4 mH
Line resistance	0.3 Ω
Grid L-L voltage	220 v
Switching frequency	8kHz
Filter inductance	1 mH
Filter resistance	0.1 Ω
DC side capacitor	2 mF
DC side inductance	0.2 mH
Virtual rotor momentum (J)	10
K_q	0.0001
K_d	1000
K_f	10
K_{qi}	0.00025
τ_v	0.005
ω_c	200 (rad/s)

a) Rectification Mode

The transient behavior of the proposed system in rectification mode is presented. When there is a sudden rise in the load at t=0.8s, the dc voltage drops from the reference value due to transients from the coupling of weak grid. This also affects the reactive power but the load angle remains constant. However the proposed system shows fast response by regulating the dc voltage and reactive power value to their preset reference value within a short period. When the reactive power is increased at t=2.5s, the VSC acting as a rectifier in this mode absorbs the reactive power from the grid. This has less recognizable variation on the dc-link voltage as the real and reactive power are decoupled and the system tracks the newly set value within a second. At t=4s, the DC-link voltage is varied from its reference value despite of its fast response the reactive power varies. As shown in fig 4.

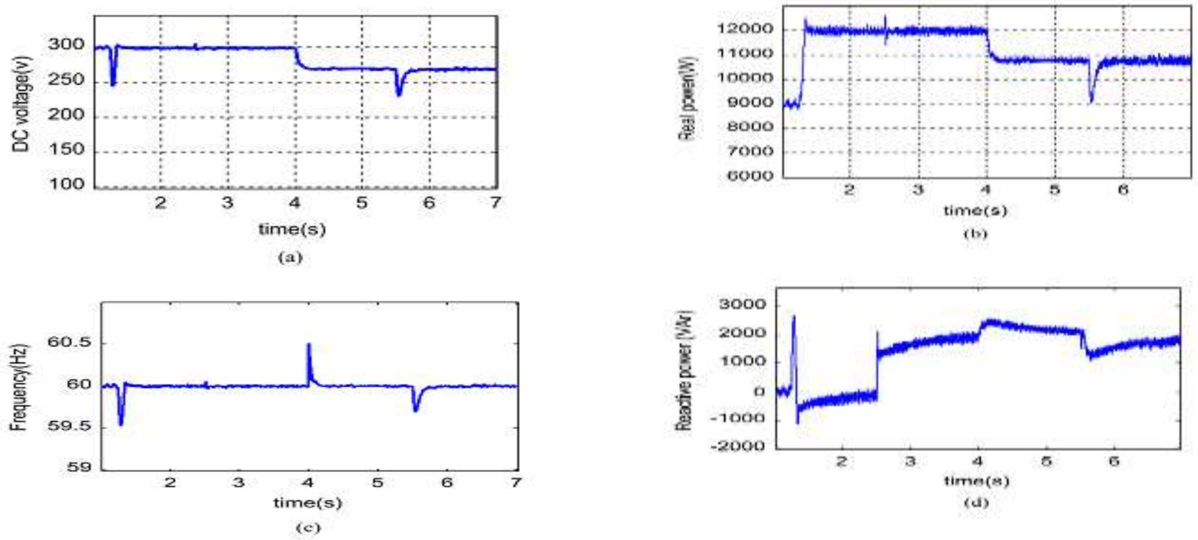


Fig.4. Simulation results for rectifying mode. (a) DC voltage. (b) Real power. (c) Frequency. (d) Reactive power.

b) Inverting Mode

Assuming the distributed generator unit is connected the dc side with its output power time variant. The proposed system has inherent dc-link voltage regulation; the VSC transfers the available power of the source the grid. When the output dc current of the DG unit is increased at t=2s, the dc link voltage shows well damped transient response. At t=3s, when the grid voltage sag occurs, this disturbance is successfully damped by the controller without any considerable effect on the real power and dc-link voltage. The controller takes fraction of a second to reset the dc-link voltage to its reference value after the DG output power is increased. As shown in fig 5.

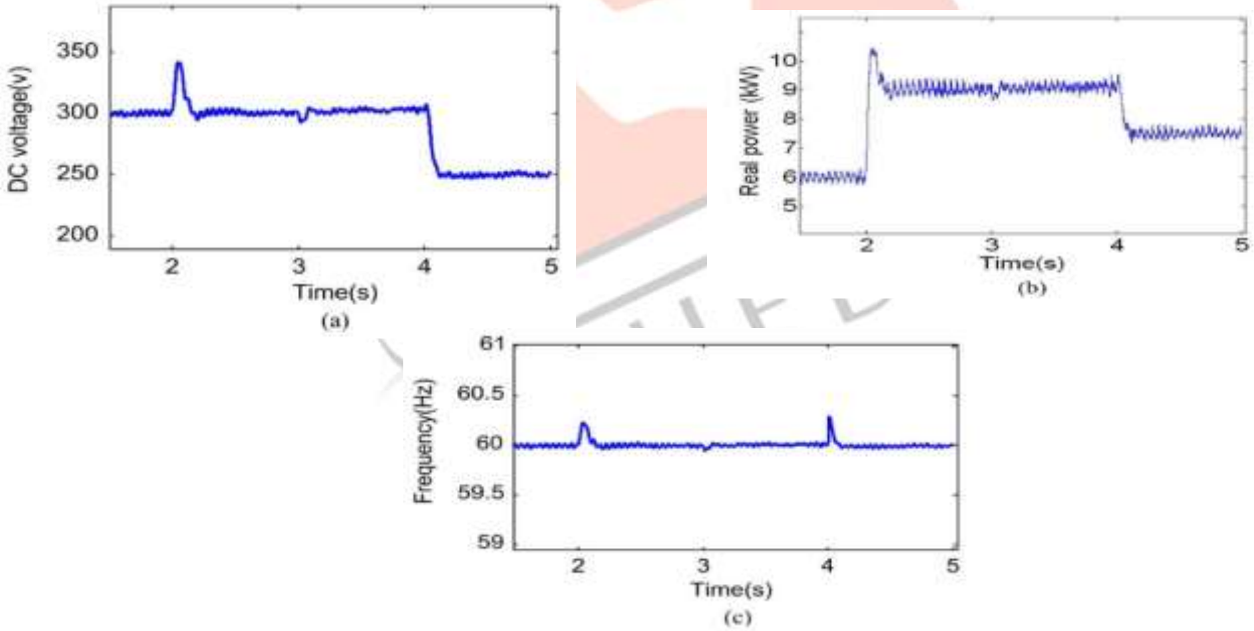


Fig.5. Simulation results for inverting mode. (a) DC-link voltage. (b) Real power. (c) Frequency.

c) Fault-Ride-Through Capability

The proposed system is designed to emulate the synchronous machine characteristics, it shows the ability to operate and synchronize themselves with the grid during and subsequent to stable faults. When an unsymmetrical single phase to ground fault occurs, the VSC operates in rectification mode. During the fault the dc-link voltage is reduced from its pre-set reference value whereas in the faulty phase the voltage is zero due the short circuit to the ground. After the fault clearance, phase voltages return to their initial conditions with minimum transients. Without PLL the system is free of PLL dynamics. As depicted in fig 6.

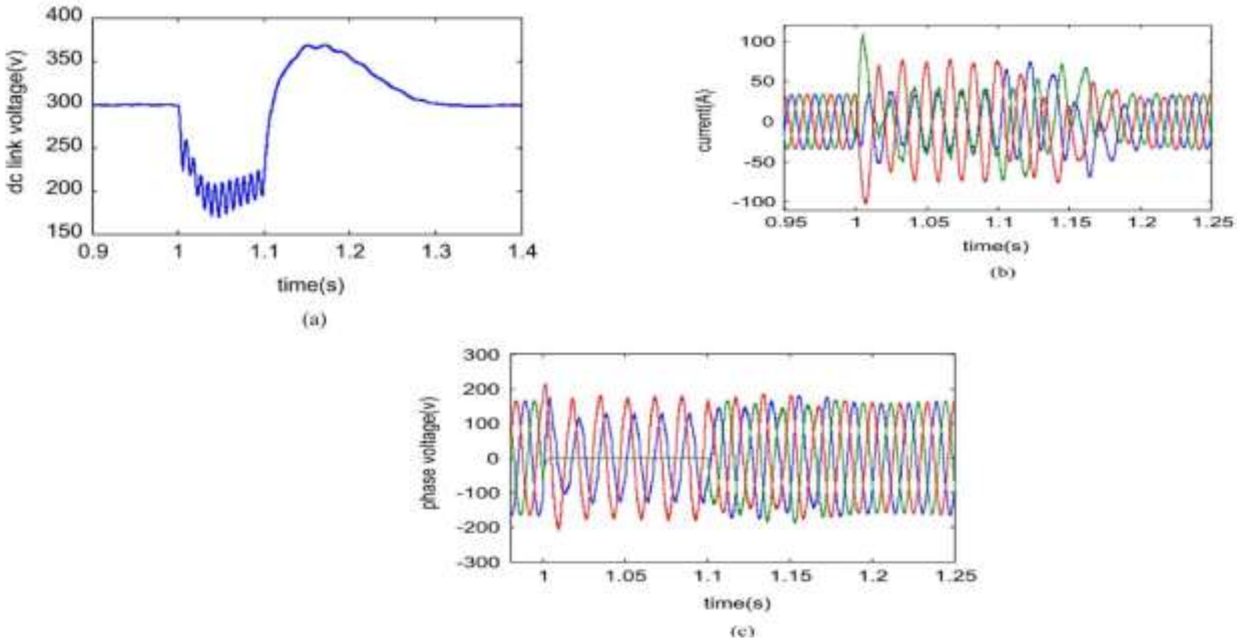


Fig.6. Fault ride through capability of the synchronous VSC. (a) DC-link voltage. (b) Instantaneous currents. (c) Instantaneous output filter voltages.

d) Virtual Torque Control Strategy

Here, the performance of the virtual torque controller, shown in Fig. 2(a), is presented. As shown in fig 2(a), based on the frequency error, the virtual torque reference is obtained and the virtual torque control loop adjusts the dc-link voltage in a way such that the damping and synchronizing torques are generated within the controller during transients similar to SMs. The parameters of the simulated system and the virtual torque control loop parameters are the same as the previous case. Also, the same scenarios of section A are applied to the system. Fig. 16 shows the dc-link voltage and frequency variation in this case. It can be seen that the controller easily tracks the dc-link voltage reference variation. Also, this controller offers good real and reactive powers decoupling capability as, when the reactive power reference is altered at $t=$ 2.5 s, there is no observable change in the dc-link voltage. The system performance indexes in terms of speed of response and frequency regulation are similar to the direct dc-link voltage controller with more under and overshoot in the dc-link voltage response but less under and overshoot in the frequency. However, the designer has more degrees of freedom to adjust the controller parameters in the virtual torque controller. Both controllers are practical and provide effective performance. As shown in fig 7.

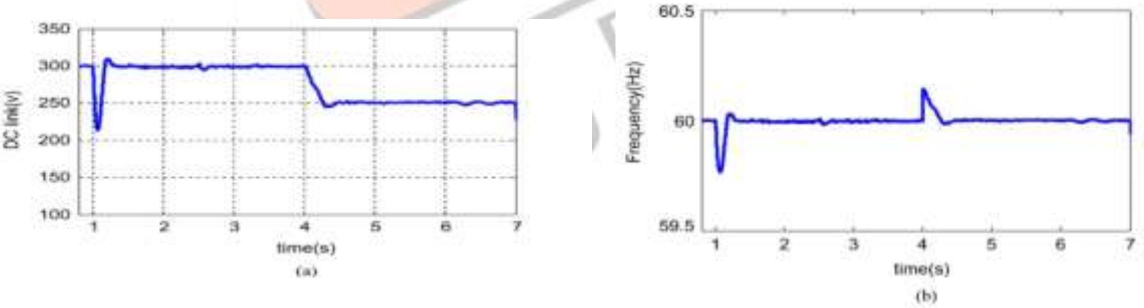


Fig.7 .System response with the virtual torque controller. (a) DC-link voltage. (b) VSC frequency.

IV CONCLUSION

In this paper, a control topology for VSCs has been developed in the frequency-angle domain to regulate the dc-link voltage while providing

1) Synchronizing and damping power components and

2) Emulated inertia function to the VSC.

These features are highly desirable in VSCs interfacing renewable energy resources, dc MGs and active converter-interfaced loads to weak ac systems.

The proposed synchronous control topology offers the following advantages.

1) It is a new control topology implemented in the frequency angle domain, which simplifies converter integration and analysis in grids with conventional SGs.

2) The controller introduces some inertia and dynamics for frequency. In fact, the power grid views the dc-link capacitor as a virtual rotor with virtual inertia. The stored energy in the dc-link is employed to damp frequency oscillations during contingencies.

3) Since the controller presents damping and synchronizing power dynamics, similar to SMs, it can automatically synchronize itself with the grid and tracks its variations, thus there is no need for a PLL after initial synchronization.

4) In the modeling and design process, the dc-link voltage dynamics are taken into account which provides a more general and accurate control framework.

5) The controller offers fault-ride-through capability which enhances the overall system reliability.

Simulation results have been provided to validate controller performance under a wide range of typical operating conditions.

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