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Emulation Strategy by Synchronous Generator for Voltage Source Converter (VSC) Stations

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Abstract:

The synchronous generator emulation control (SGEC) strategy for the VSC-HVDC station. The SGEC strategy is divided into the inner control loop and the outer control loop. The voltage source converter (VSC) station is playing a more important role in modern power systems, but the dynamic behavior of the VSC station is quite different from that of the synchronous generator.

1. The (inner controller) is developed for fast current and voltage regulations.

2. An inertia element is introduced into the frequency-power droop to determine the command reference of the frequency, and

3. The inertia response and the primary frequency regulation are emulated. In addition, the secondary frequency regulation can be achieved by modulating the scheduled power in the SGEC strategy. Therefore, the SGEC strategy provides a simple and practical solution for the VSC station to emulate the behavior of a synchronous generator.

EXISTING SYSTEM:

The existing synchronous generator has inherent features beneficial to power system stability, such as the increase in system inertia, the synchronizing power and the damping power. The (SG) synchronous generator is not only able to work in parallel with other generators, but is also able to supply a passive network.

The vector current control has been widely used in the control of the VSC-HVDC system for the fast current regulation abilities. With the constant power control, the delivered power of the VSC-HVDC system could be precisely controlled at the scheduled value, irrespective of the frequency variations of the two grids. Different application of VSC-HVDC transmission systems is to supply a weak or passive grid far away from the main grid. With the constant power control, the output power from the VSC station is controlled as a constant, and no frequency support is provided to the weak grid. When a significant part of the power in a local gird is supplied by the VSC station, the system inertia becomes lower, and changes in generation or load may cause large frequency deviations possibly leading to system instability. The continuous progress of the voltage power voltage source converter is used. more VSC based devices like VSC-HVDC transmission systems, FACTS and energy storage systems (ESS) have been installed.The VSC station is playing a more important role in modern power systems. A new concept of virtual synchronous generator, which represents a VSC operated in the similar way as the synchronous generator,

PROSED SYSTEM:

The proposed synchronous generator emulation control (SGEC) strategy includes an inner control loop and an outer control loop. Due to the fast current limiting of the inner current controller, the over-current blocking

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of the converter valves could be avoided. Only a first-order inertia element is added to the CDC strategy to determine the frequency command reference, without any additional control loop. The proposed SGEC strategy is considered as a simple and practical solution for the VSC station to imitate the behavior of a synchronous generator.

TECHNOLOGY:

The following technology is used in the paper:

- High-voltage direct-current (HVDC) transmission.
- Modular multilevel converter (MMC).
- Synchronous generator (SG) emulation.
- Vector control.
- Virtual synchronous generator.
- Voltage source converter (VSC) station.
- VSC-HVDC.

The two VSC stations, denoted by VSC1 and VSC2, are linked by a pair of DC cables. Each VSC station is connected to the AC system through an interfacing reactor and a converter transformer. The converter reactor blocks the high-frequency harmonic currents generated by the VSC station from entering into the power system, while a high-pass (HP) filter is installed at the PCC to provide a low-impendence path to ground for the high-frequency harmonic currents. The converter reactor and the HP filter constitute a low-pass filter system. Because a large portion of power is supplied by the VSC station, the inertia of the local grid is significantly reduced. It becomes especially beneficial to the frequency stability of the local grid that the VSC station can provide frequency support.

Block diagram:

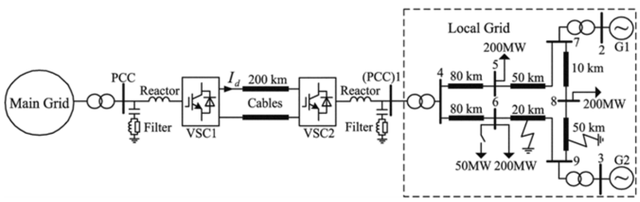

Fig.1 Schematic diagram of a VSC-HVDC transmission system supplying a small local grid.

Technique of control:

A large portion of power is supplied by the VSC station, the inertia of the local grid is significantly reduced. It becomes especially beneficial to the frequency stability of the local grid that the VSC station can provide frequency support.

- VSC Model
- Inner Control Loop

The AC-side of different VSCs can be generally represented by a three-phase AC voltage source. In conventional VSCs like the two-level converter and the neutral point clamped (NPC) converter, L and R are the inductance and resistance of the interfacing reactor [22]. In modular multilevel converter (MMC), L and R are half of the inductance and resistance of the arm reactor. The HP filter is considered purely capacitive at the fundamental frequency, and its equivalent capacitance is represented by C.

According to Fig. 2, the AC-side dynamics of different VSCs are generally expressed as

$$L\frac{d\mathbf{i}_{\mathbf{abc}}}{dt} + R\mathbf{i}_{\mathbf{abc}} = \mathbf{v}_{\mathbf{abc}} - \mathbf{u}_{\mathbf{abc}}$$

$$C\frac{d\mathbf{u}_{\mathbf{abc}}}{dt} = \mathbf{i}_{\mathbf{abc}} - \mathbf{i}_{\mathbf{Labc}}$$

Where:

Vabc and Iabc are the column vectors of the three-phase output voltages and currents from the VSC, and and are the column vectors of the three-phase output voltages and currents at the PCC. The balanced three-phase voltages and currents can be transformed to the synchronous dq-axis voltage and current components via the following Park transformation:

$$\mathbf{u}_{\mathbf{dq}} = \mathbf{T}\mathbf{u}_{\mathbf{abc}}$$

$$\mathbf{T} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix}$$

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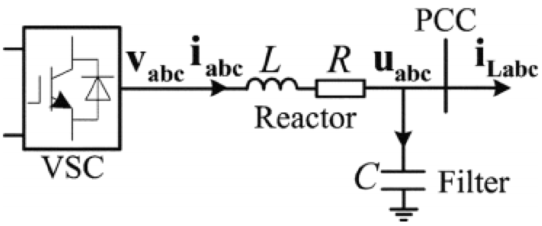

Fig. 2.AC-side of a VSC station.

The AC-side dynamics of the VSC station, in term of the dq-axis components, are expressed as below

$$L\frac{di_d}{dt} = Ri_d + \omega L i_q + v_d - u_d$$
$$L\frac{di_q}{dt} = -\omega L i_d - Ri_q + v_q - u_q$$
$$C\frac{du_d}{dt} = \omega C u_q + i_d - i_{Ld}$$
$$C\frac{du_d}{dt} = -\omega C u_d + i_q - i_{Lq}.$$

B. Inner Control Loop:

The inner control loop is a vector control scheme including a current controller and a voltage controller. Because the vector control scheme has been widely used in the control of VSC, only a brief description is given here. The inner current controller is given by below equations

$$v_d = u_d - \omega^* L i_q + (k_{p1} + \frac{k_{i1}}{s})(i_d^* - i_d)$$
$$v_q = u_q + \omega^* L i_d + (k_{p1} + \frac{k_{i1}}{s})(i_q^* - i_q)$$

where*W**is the frequency reference of the outer control loop Kp1, and ki1 represent the proportional and integral gains, respectively. Since the VSC has very little over-current capability, a large transient current due to disturbances will stress or damage the valves [2]. If the value of the dq-axis current command references *i*d*and*i*q* are limited, the fast-response current controller is effective in preventing the VSC from over-current blocking.

The voltage control mode is designed to control the AC voltages at the PCC, which can be regulated by the charging of the capacitive filter. Thus, the current command references *i*d* and *i*q* of the inner current control are given by

$$i_d^* = -\omega^* C u_q + (k_{p2} + \frac{k_{i2}}{s})(u_d^* - u_d)$$
$$i_q^* = \omega^* C u_d + (k_{p2} + \frac{k_{i2}}{s})(u_q^* - u_q).$$

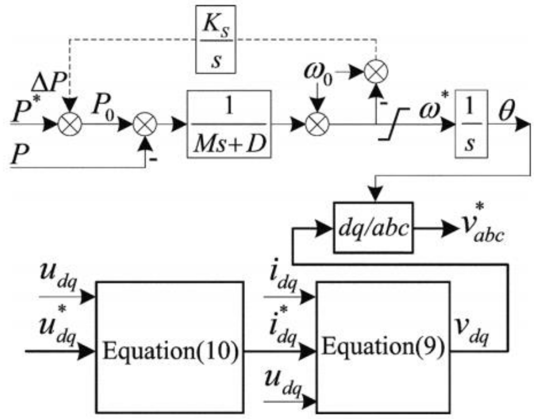

Fig. 3. Overall control scheme of the SGEC strategy.

Where U* is the nominal amplitude of the PCC voltage. The inner control scheme is illustrated in Fig. 3.

C. Outer Control Loop:

The inductive component of the line impedances in high voltage (HV) networks is typically much higher than the resistive one, and the value of the real power delivered to the grid can be regulated by controlling the frequency of the voltages at the PCC. The outer control loop is developed to regulate the angular frequency of the PCC voltages, in which the synchronizing signal for the Park transformation is

$$\theta = \int_{\tau=0}^{t} \omega^* d\tau + \theta_0$$

Where *W** is the command reference of the angular frequency of the PCC voltages.

The three-phase voltages at the PCC are derived by the inverse Park transformation in (14):

$$\mathbf{u_{abc}} = \mathbf{T}^{-1}\mathbf{u_{dq}}$$

$$\mathbf{T}^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta-\frac{2\pi}{3}) & -\sin(\theta-\frac{2\pi}{3}) \\ \cos(\theta+\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3}) \end{bmatrix}.$$

Thus, the phase-a voltage is expressed as

$$\begin{aligned} u_a(t) &= u_d\cos\theta - u_q\sin\theta \\ &= \sqrt{u_d^2+u_q^2}\cos\left(\theta+\tan^{-1}(\frac{u_q}{u_d})\right). \end{aligned}$$

The differentiation of the phase angle in (15) is the angular frequency

$$\omega = \omega^* + \frac{1}{u_d^2+u_q^2}\left(u_d\frac{du_q(t)}{dt} - u_q\frac{du_d(t)}{dt}\right).$$

Because the differentiations of the dq-axis voltage components at the PCC in steady state are both zero, the second term in above equation is a transient component. Thus, the angular frequency of the PCC voltages could track its command reference in steady state with the outer control loop.

D. Synchronous Generator Emulation Control:

To emulate the swing equation, the command reference of the angular frequency of the PCC voltages can be determined as

$$M\frac{d\omega^*}{dt} = P_0 - P - D(\omega^*-\omega_0).$$

In the swing equation, P0 and P are the mechanical input power and the electrical output power, M and D are the inertia coefficient and the damping power coefficient, and *W0* is the nominal angular frequency. Applying the Laplace transform, for the above equation.

$$P_0 - P = Ms\omega^* + D(\omega^*-\omega_0) = (Ms+D)(\omega^*-\omega_0).$$

In the SGEC strategy, the command reference of the angular frequency can be derived from above eq:

$$\begin{aligned} \omega^* &= \omega_0 - \frac{P-P_0}{Ms+D} \\ &= \omega_0 - \frac{1}{1+\frac{M}{D}s}\frac{P-P_0}{D} \\ &= \omega_0 - \frac{1}{1+Ts}\frac{P-P_0}{D} \end{aligned}$$

In which the lag time of the first order inertia element is de- fined as $T = \frac{M}{D}$.

If the lag time T is 0, (20) is simplified as

$$\omega^* = \omega_0 - \frac{P-P_0}{D}$$

Which represents the CDC strategy. In the CDC strategy, is the droop coefficient. and are the actual and scheduled real power outputs from the PCC to the grid, respectively. Comparing from above two equation the SGEC strategy is realized only by adding a first-order inertia element to the widely used CDC strategy, without any additional control loops. Only one additional control parameter (i.e., the lag time in the first-order inertia element) is required, so the SGEC strategy is considered much simpler than the previous strategies

Working principle:

A. Swing Equation
B. Primary Frequency Regulation
C. Secondary Frequency Regulation

Swing Equation :

The SGEC strategy of (19) can be rewritten as

$$\omega^* = \omega_0 + \frac{1}{1+Ts}\frac{P_0}{D} - \frac{1}{1+Ts}\frac{P}{D}.$$

(22) The first term in (22) is a constant.

In the SGEC strategy, the scheduled and actual powers are filtered by the first-order inertial element. rewritten as

$$M\frac{d\omega^*}{dt} = P_0 - P - D(\omega^*-\omega_0).$$

When the scheduled output power is greater than the actual output power, the frequency reference will be gradually increased. On the contrary, the frequency reference will be gradually decreased, when the scheduled power is lower than the actual value. The damping power is proportional to the deviation of the frequency reference from the nominal frequency. It should be noted that an increase in the inertia decreases the oscillation damping like that in a synchronous generator. Taking the single-machine infinite bus system as an example, the damping ratio of the characteristic equation is represented by

$$\zeta = \frac{D}{2\sqrt{MK_E}} \quad \zeta = \sqrt{\frac{D}{4TK_E}}.$$

The inertia is increased, but the oscillation damping is reduced for the larger lag time in the SGEC strategy.

Primary Frequency Regulation:

the frequency deviation in steady state is given by

$$\Delta\omega = \omega - \omega_0 = -\frac{P - P_0}{D} = -\frac{\Delta P}{D}.$$

Thus, there is a droop relationship between the frequency and the output power, which is the same as that of the primary frequency regulation of a synchronous generator. Thus, the frequency of the VSC station is adjustable, which can coordinate with other generators or supply a passive network [19]–[21]. When the converter output power is equal to the scheduled power, the frequency of the PCC voltage will settle down at the nominal value. Otherwise, the frequency of the PCC voltage is changed in proportional to the deviation of the real power from the scheduled value. In consequence, the VSC station is able to provide primary frequency regulation to the local grid.

Secondary Frequency Regulation:

In an isolated power system, the secondary frequency control is adopted in certain synchronous generator to restore the system frequency to the nominal value, which is accomplished by adding a slow-response integral term acting on the mechanical power reference of the speed governor [30]. As shown in Fig. 3, the secondary frequency regulation could be realized by adding a slow-response integral term to modulate the scheduled power of the converter:

$$P_0 = P^* + \Delta P.$$

Where P* is the initial scheduled power set by the system operator. Therefore, the SGEC strategy provides the VSC stations with a simple and practical solution for the emulation of synchronous generators.

MODE OF OPERATION:

The MMC is an emerging and attractive VSC topology for HVDC applications. The schematic diagram of the study system is illustrated in Fig. 1, and the power is delivered from the main grid to the local grid by an MMC-HVDC transmission system. Detailed model of the MMC-HVDC system is implemented in the PSCAD/EMTDC software environment, and the parameters are listed in Table I. The control parameters of the CDC and SGEC strategies are given in Table II. A modified 3-machine 9-bus system is adopted as a typical case of the local grid, in which a large synchronous generator is replaced by the inverter station.The parameters of the other two synchronous generators are listed in Table III. The performances of the local grid with the CDC and SGEC strategies under different operation cases are investigated and compared by PSCAD/EMTDC simulations.

Condition 1: Steady-State Operation

The steady-state operation is considered in the first case. The output powers to the local grid from the VSC station, the generator G1 and the generator G2 are 350 MW, 150 MW, and 100 MW, respectively. The control strategy of the VSC station is changed from the CDC strategy to the SGEC strategy at t=9 s. Because there is no real rotating component in the converter, the frequency reference given by the controller is considered as the frequency of the VSC station.

Condition 2: Load Changes

The most common disturbance in a power system is the load change. Due to the lack of inertia, an

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unbalance in the power generation and consumption will result in a large system frequency excursion.
As shown in Fig. 6, the frequency drop of the VSC station under the SGEC strategy is slower and smoother than that under the CDC strategy. As a result, the frequency drops of two synchronous generators under the SGEC strategy are also slower than that under the CDC strategy. Due to the inertial characteristics, the maximum frequency drops of the VSC station, G1 and G2 are reduced by the SGEC strategy. After a short period of transient, the frequency of the local grid can be restored to the nominal value by the secondary frequency regulation from G1. Thus, the system inertia could be increased by the SGEC strategy. If the secondary frequency regulation is provided by the VSC station, the corresponding responses of the study system with the two control strategies are illustrated in Fig. 7. After a short period of transient, the frequency of the local grid can be also restored to the nominal value by the secondary frequency regulation from the VSC station. The output power of the VSC station is increased by 50 MW to supply the additional load. Thus, the VSC station is able to provide second frequency regulation to a low-inertia grid.

Condition 3: AC Fault

The disturbance in this case is a three-phase grounding fault occurring in the middle of line 6–9, which is near the VSC station. The fault is cleared in five cycles (0.1 s) by opening line 6–9. The dynamic performances of the study systems in response to this three-phase fault are illustrated in Fig. 8. When the three-phase fault happens at t=10 s, the output powers of the VSC station with the two control strategies are decreased almost to zero. As a result, the frequency of the VSC station with the CDC strategy is suddenly changed to the upper limit, and the frequencies of G1 and G2 are both accelerated to about 51.3 Hz. In contrast, the frequency of the VSC station with the SGEC strategy is gradually changed, and the frequencies of G1 and G2 are accelerated to about 50.5 Hz and 50.7 Hz. After the fault is cleared, the output powers of the VSC stations are gradually restored, and the VSC station and the generators settle down to new steady-state conditions. During the transient period, the frequency deviations of the VSC station and the generators with the SGEC strategy are much smaller than that with the CDC strategy. The other disturbance is a three-phase grounding fault occurring in the middle of line 8–9, which is far away from the VSC station. The fault is cleared in five cycles (0.1 s) by opening line 8–9. The dynamic performances of the study systems in response to this three-phase fault are illustrated in Fig. 9. During the transient period, the frequency deviations of the VSC station and the generators with the SGEC strategy are also much smaller than that with the CDC strategy. Therefore, the SGEC strategy is effective in increasing the system inertia and reducing frequency deviations of a low-inertia grid.

TABLE I
PARAMETERS OF MMC-HVDC SYSTEM

Quantity	Value
Nominal DC voltage	+/- 200 kV
SMs per arm	20 SMs
Rated apparent power	450 MVA
Rated AC system voltage	230 kV
Rated AC system frequency	50 Hz
Converter transformer rating	450MVA
Transformer ratio	210 kV/230 kV
Transformer leakage inductance	10 %
Converter arm inductance	40 mH
Sub-module capacitance	3000 uF
HP Filter capacitance	5 uF
Cable model	Frequency dependent (phase)
Cable length	200 km

TABLE II
CONTROL PARAMETERS

Quantity	CDC Strategy	SGEC Strategy
D	20	20
Lag time, $T(M/D)$	0.005 s	0.3 s
K_S	50	50
Frequency limits	50±2 Hz	50±2 Hz
Scheduled power	350 MW	350 MW

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TABLE III
PARAMETERS OF SYNCHRONOUS GENERATORS

Quantity	Value
Rated real power	G1:250 MW, G2: 150MW
Rated AC voltage	13.8 kV
Rated AC current	G1: 10.47 kA, G2: 6.54 kV
Inertia constant	G1: 2.6 s, G2:1.8s
Governor and turbine: R	0.05
Governor and turbine: T_R	1 s
Exciter: K_a	200
Exciter: T_a	0.01 s
Step-up transformer rating	G1: 250 MVA, G2: 150MVA
Transformer ratio	13.8 kV/230 kV
Transformer leakage inductance	10 %

CONCLUSION:

The synchronous generator emulation control strategy is proposed for the VSC station, by which the behavior of a synchronous generator can be emulated. The control scheme is divided into two separate loops: an inner control loop and an outer control loop. The inner controller is a conventional vector controller developed for the fast current control and the PCC voltage regulation. In the outer controller, the conventional droop control is modified by introducing a first-order inertia element. The lag time of the inertia element is intentionally increased to provide the inertia response. As a result, the frequency regulation of the SGEC strategy is found to be a nice analogy to the swing equation of a synchronous generator. Moreover, the primary and secondary frequency regulations are also realized by the SGEC strategy. Therefore, the frequency support can be provided by the VSC station with the SGEC strategy, which is especially desired to a low-inertia gird

SOFTWARE TOOLS:

(Matlab Simulation)

Simulink

- It is a commercial tool for modeling, simulating and analyzing multi domain dynamic systems.
- Its primary interface is a graphical block diagramming tool and a customizable set of block libraries.
- Simulink is widely used in control theory and digital signal processing for multi domain simulation and Model based design.

APPLICATIONS:

1.Technical computing
2.Engineering and sciences applications

- Electrical Engineering
- DSP and DIP
- Automation
- Communication purpose
- Aeronautical
- Pharmaceutical
- Financial services.

Other Features

- 2-D and 3-D graphics functions for visualizing data
- Tools for building custom graphical user interfaces
- Functions for integrating MATLAB based algorithms with external applications and languages, such as C, C++, FORTRAN, Java, COM, and Microsoft Excel.

ADVANTAGES:

The time-domain simulation results demonstrate the VSC station with the proposed control strategy can provide desired frequency support to a low-inertia grid. Therefore, the SGEC strategy provides a simple and practical solution for the VSC station to emulate the behavior of a synchronous generatorNovel control techniques are presented, by which the VSC station is able to provide the inertial response, the frequency regulation, and/or the power system damping

APPLICATION:

The continuous progress of the high-voltage high-power voltage source converter (VSC) technologies,

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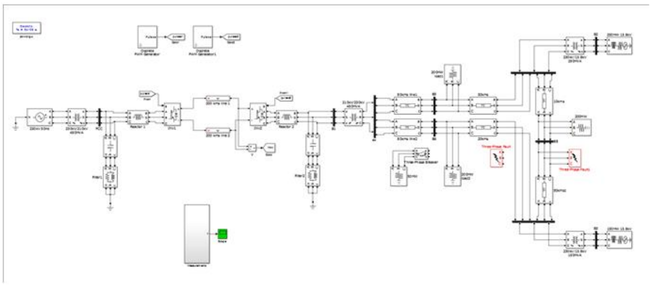
more and more VSC based devices like VSC-HVDC transmission systems, flexible AC transmission systems (FACTS) and energy storage systems (ESS) have been installed, and the VSC station is playing a more important role in modern power systems. The transmission rating up to several hundred MW has been reached in recent VSC-HVDC projects.

CONVERTER DESIGN:

SIMULINK RESULTS AND OUTPUTS



Simulation block diagram

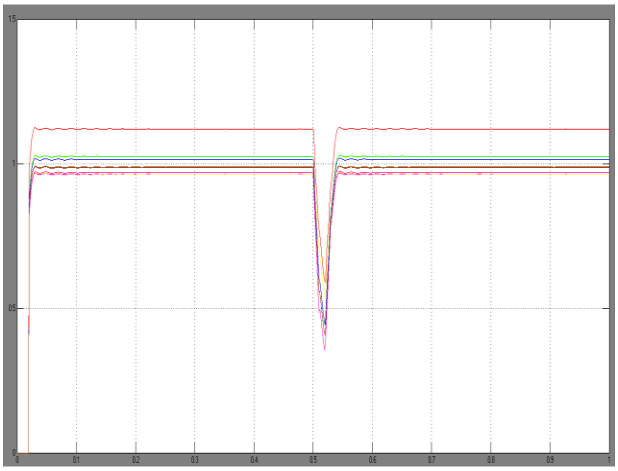


Figure 2:Voltage magnitudes

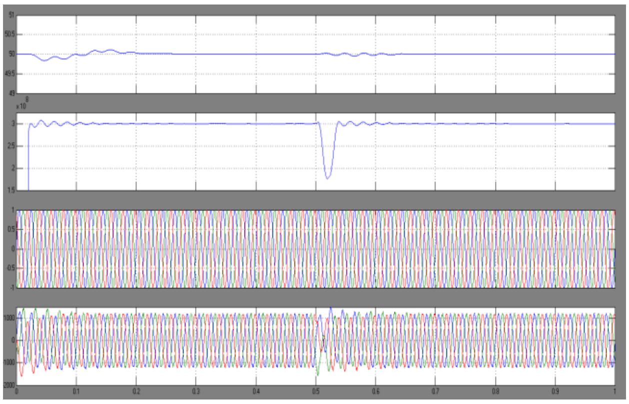


Figure 3: a) Frequency at local side grid b)active power c) Vabc at PCC d) Iabc at Pcc

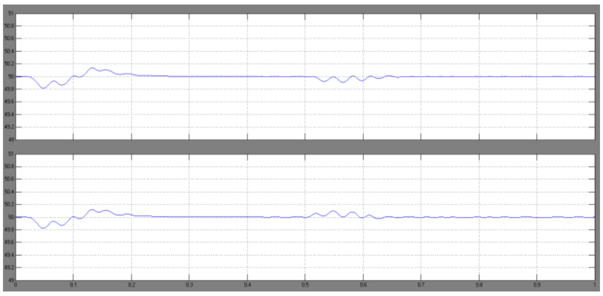


Figure 4: frequency at G1and G2

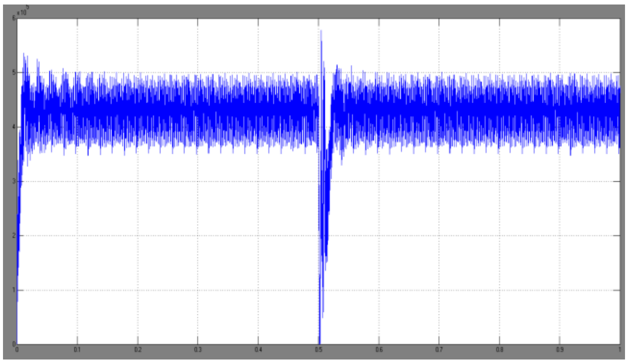


Figure 5: V dc DC voltage between the voltage source converter

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