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Mathematical Modelling and Simulation of Voltage Source Converter

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Abstract

This research provides the mathematical modeling and simulation of a Voltage Source Converter (VSC) employed in advanced power systems for effective DC to AC voltage conversion. The research investigates the dynamics of VSCs, emphasizing important components like Pulse Width Modulation (PWM), dq current control, and PI controllers, coupled with an LCL filter for harmonic suppression. The control strategies, voltage and current regulation are proven using simulation responses with stable and precise output voltage and current. The results confirm the significance of robust control algorithms in obtaining optimum system performance and lay a groundwork for further study.

Keywords: Voltage Source Converter, dq Control Strategy, Clarke's Transformation, Park's Transformation, Inner Loop Control.

1. Introduction

Voltage Source Converters (VSCs) are now essential components of contemporary power systems and industrial processes, facilitating the conversion of DC voltages to controllable AC voltages for power transmission and control with high efficiency [1]. VSCs play a key role in grid interfacing, especially in High Voltage Direct Current (HVDC) transmission systems and renewable energy systems. VSC dynamics involve intricate interactions between electrical and control components, which must be well modelled mathematically to analyze system behavior, performance, and control [2]. Mathematical

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models and simulation are key tools for engineers and researchers to design, optimize, and test VSC systems without physical models.

With the addition of control techniques like Pulse Width Modulation (PWM), dq current control [3], and PI controllers, VSCs can be utilized to modulate the output voltage and currents with precision and thereby facilitate stable and efficient operation. Additionally, the addition of an LCL filter [4] removes harmonic distortions, thus facilitating improved overall system performance. Simulation tools like MATLAB/Simulink offer a platform through which the provided control techniques can be simulated and tested, and thus assist engineers in assessing system stability as well as grid code compliance before actual power system implementation. Mathematical modelling and simulation of VSCs are presented and discussed in this research, including associated control algorithms, system dynamics, and filter design influence on overall performance. Findings of the current work are anticipated to further improve VSC technology and integration with modern power systems.

2. Voltage Source Converter

Figure 1 illustrates the role of the LCL filter and control strategy in the VSC. The main role of the VSC is to transform the constant DC voltage to an AC voltage. The AC voltage is needed in driving AC loads for interfacing with AC power systems. Using power semiconductor devices like Insulated-Gate Bipolar Transistor (IGBTs), the VSC is utilized in rectification and inversion modes, AC to DC and DC to AC, respectively. In conjunction with an LCL filter for the reduction of harmonic distortions. The VSC utilizes Pulse Width Modulation (PWM) [5] techniques to modulate voltages with high precision, ensuring output stability and efficiency. It controls the output AC voltage based on desired setpoints. This ensures that the loads connected are supplied with the necessary voltage levels for efficient operation [6-10].

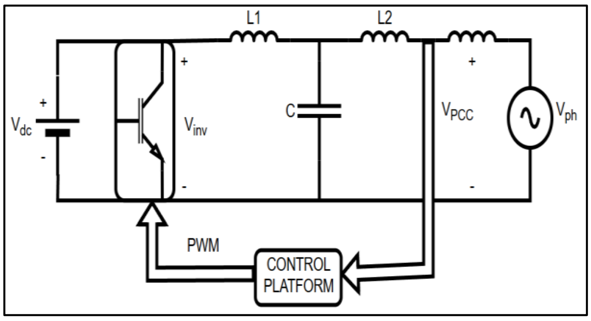

Figure 1. Block Diagram of the VSC

3. Control Strategies

3.1 Voltage Control Method

Voltage controller in a VSC system ensures the output voltage to be exactly the same as the desired reference voltage. It is one of the control methods that ensure stability and performance of the VSC in providing power to the load. It involves the generation of reference voltages based on the needs of the system and comparing them with actual voltages to generate error signals. The task of this voltage controller is to maintain the output voltage $Vabc$ at the referenced value. PI controllers are used to control the modulation index of the PWM signals so that the output voltage follows the desired reference voltage exactly. The inverse dq transformation is used to convert regulated Vd and Vq into $Vabc$ to be used in PWM modulation

3.2. dq Current Control

To control the AC currents supplied by the VSC, dq current control is utilized. It is achieved through the conversion of the three-phase currents (abc) to the synchronous reference frame (dq) where the direct axis is aligned along the dc component of the current and the quadrature axis is aligned along the ac component. Proportional-integral (PI) controllers are often utilized in the dq domain for controlling the currents and keeping reference values desired.

3.3. LCL Filter Control

With the addition of an LCL filter to the system, other control techniques are employed to damp the harmonics and offer stability. This may involve the utilization of damping controllers or active damping techniques to dampen resonance and offer system stability.

4. Design and Modelling of VSC

4.1 Clarke's Transformation

The Clarke's transformation converts three phase quantities (e.g., voltages, currents) from the abc reference frame to the stationary $\alpha\beta$ reference frame. Simplifies control algorithms by transforming three phase signals into two orthogonal components. These components are easier to manipulate and control, particularly in systems like the VSC where dq control is employed.

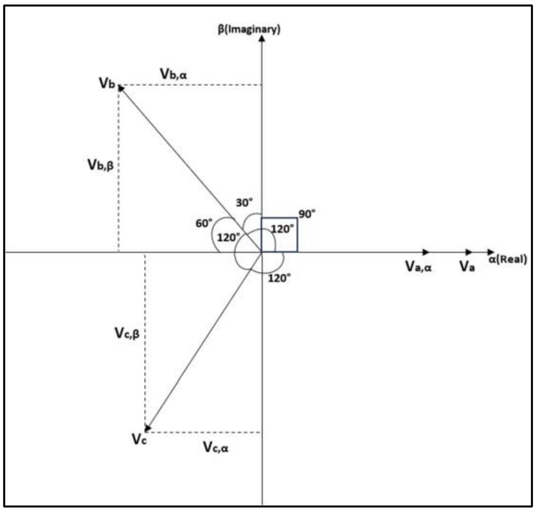

Figure 2. Representation of Clarke's Transformation

Figure 2 represents the transformation of three phase quantities into two phase quantities.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

This equation (1) gives the transformation of three phase quantities ($Vabc$) into two phase reference frame ($V\alpha\beta$).

4.2 Park's Transformation

The Park transformation rotates the $\alpha\beta$ reference frame into the dq reference frame, which is synchronous with the rotating electrical angle of the system. This transformation facilitates decoupled control of active (d-axis) and reactive (q-axis) components of the system, enabling independent control of real and reactive power. The transformation of αβ reference frame into dq reference frame and is represented in Figure 3.

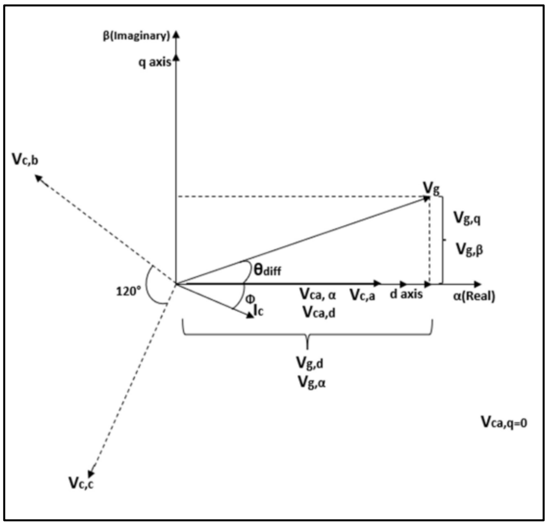

Figure 3. Representation of Park’s Transformation

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} \qquad (2)$$

This equation (2) gives the transformation of αβ reference frame into the dq reference frame,

4.3 Modelling of VSC

The dynamics of the VSC ac side variables can be described in an abc frame as equation (3),

$$v_{t,abc} = R_t i_{t,abc} + L_t \frac{di_{t,abc}}{dt} + v_{abc} \qquad (3)$$

Transforming (1) from the abc frame to a stationary $\alpha\beta 0$ frame given as equation (4),

$$v_{t,abc} = R_t i_{t,\alpha\beta 0} + L_t \frac{di_{t,\alpha\beta 0}}{dt} + v_{\alpha\beta 0} \qquad (4)$$

Using the following synchronously rotational reference frame transformation:

$$\begin{bmatrix} v_{t,d} \\ v_{t,q} \\ v_{t,0} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) & 0 \\ -\sin(\omega t) & \cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{t,\alpha} \\ v_{t,\beta} \\ v_{t,0} \end{bmatrix} \qquad (5)$$

From equations (5) and (6)

$$v_{t,dq} = Ri_{t,dq} + L \frac{di_{t,dq}}{dt} + j\omega L i_{t,dq} \qquad (6)$$

Substituting the complex values of $vt,dq = vt,d + jvt,q,\ vs,dq = vs,d + jvs,q, and\ it,dq = it,d + jit,q$

The voltage equations can be expressed as equation (7) and (8):

$$v_{t,d} = Ri_{t,d} + L\frac{di_{t,d}}{dt} - \omega Li_{t,q} + v_{s,d} \qquad (7)$$

$$v_{t,q} = Ri_{t,q} + L\frac{di_{t,q}}{dt} + \omega Li_{t,d} + v_{s,d} \qquad (8)$$

4.4 Inner Loop Control

Inner loop control is typically utilized to define the control techniques adopted in the VSC for governing such values like voltages or currents. Inner loop control plays an important function in the maintenance of the intended performance of the VSC system, especially in applications requiring rapid and accurate control.

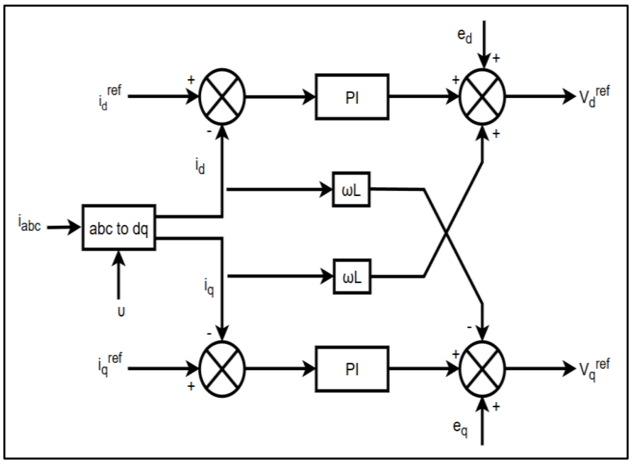

Figure 4. Inner Loop Controller Implemented in Synchronous Reference Frame

$$\frac{d}{dt}\begin{bmatrix} i_{t,d} \\ i_{t,q} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} i_{t,d} \\ i_{t,q} \end{bmatrix} + \frac{1}{R}\begin{bmatrix} u_d \\ u_q \end{bmatrix} \qquad (9)$$

The quadratic and direct axes are decoupled in Figure 4. However, as model parameter uncertainties and system mismatch, the axes will not be fully decoupled in practice.

The decoupling transfer function of the system for all the axes is the same as

$$G_s(s) = \frac{K}{1+sT} \qquad (10)$$

Design of the PI controller is based on the open-loop transfer function of the current control loop is given in equation (11)

$$G_O(s) = \left[\frac{1+sT_n}{sT_i}\right]\left[\frac{K_{cm}}{1+sT_{pE}}\right]\left[\frac{K_s}{1+sT_s}\right] \qquad (11)$$

5. Simulation of VSC

5.1 Design parameters

In a VSC design for an application of 800 V DC link voltage and 5 kVA inverter rating [5], some of the critical parameters must be selected judiciously to offer optimal performance and stability. The following Table.1 demonstrates the design parameters used in this research.

Table 1. Parameters for Designing the VSC Model

DC Voltage (Vdc)	800 V
Desired output voltage	415 V
Inverter rating	5 kVA
PWM Parameters	
Modulation Index (m)	0.9
Controller Parameters	
Kpd , Kpq	0.1
Kid , Kiq	10
Filter Parameters	
Inductance (L1)	5 mH
Inductance (L2)	3 mH
Capacitance (C)	50 μ F

5.2 Simulation of VSC

Simulation of a VSC is a critical step in the comprehension and verifying its ability to convert DC power to AC power. The design and simulation of the VSC with the following:

DC link voltage of 800 V and 5 kVA rated inverter, an LCL filter to reduce harmonics, and control methods such as PWM, dq current regulation, voltage control and PI regulators is depicted in Figure 5.

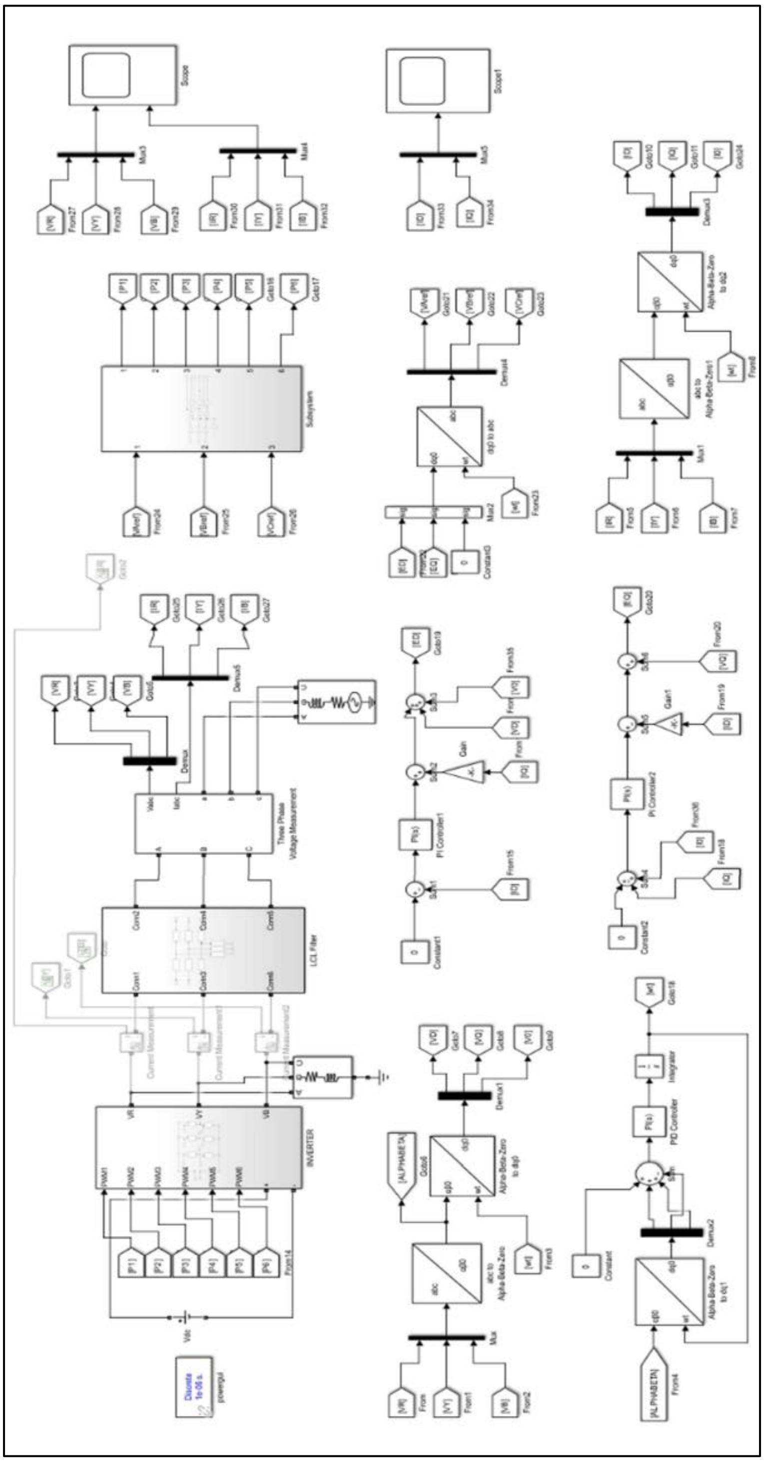

Figure 5. Simulation of VSC

5.3 Detailed View of dq Control Block

The Clarke’s and Park’s transformations enable simpler and more effective control of the VSC’s output currents and voltages. The simulation of a VSC with dq current and voltage control including Clarke’s and Park’s transformations typically involves several interconnected blocks that together regulate the output voltage and current.

5.4 Simulation Outputs

Figure 6 represents the effectiveness of the voltage control strategy. The peak amplitude of Va, Vb, Vc were each approximately 390 V, indicating that the system effectively regulated the output voltage to the desired level.

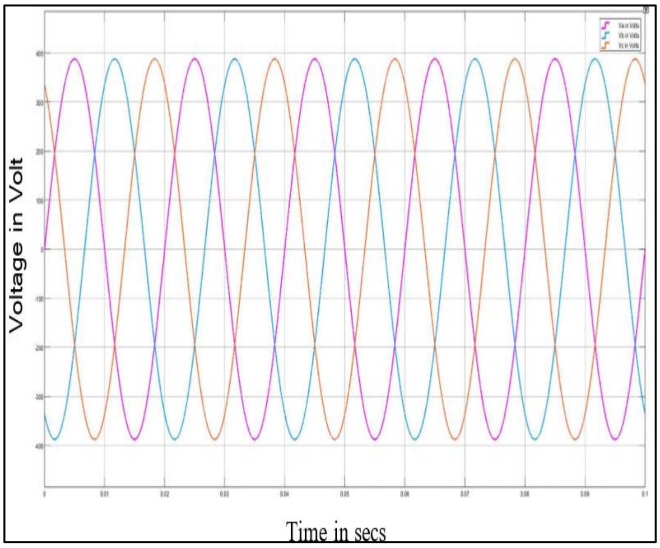

Figure 6. Three Phase Voltage Output

The RMS current values matches the load requirements, with the 5 kVA rating of the inverter and the 800 V DC input. The simulation in Figure 7 shows that the RMS values of Ia, Ib and Ic were approximately 6.15 A, indicating correct current regulation according to the load.

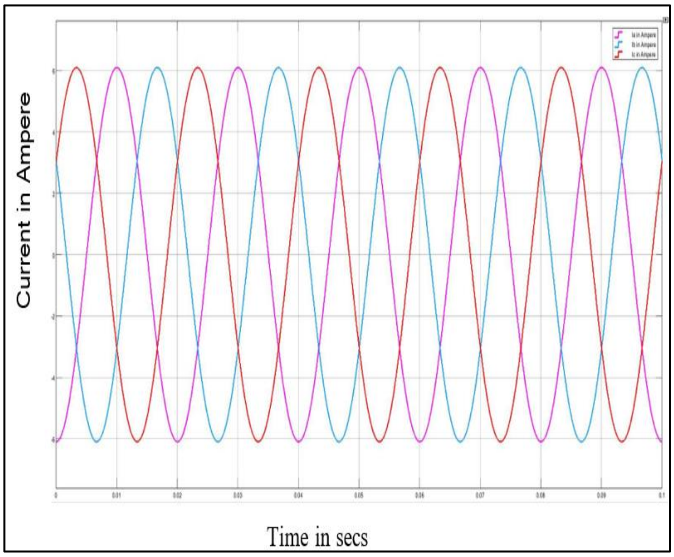

Figure 7. Three Phase Current Output

The below Figure 7 describes the behaviour of i_d and i_q over time. The transient's overshoot at the peak current of 6.15 A and attains the steady state at 0.0025 secs. The simulation depicts how well the control system maintains the desired current levels.

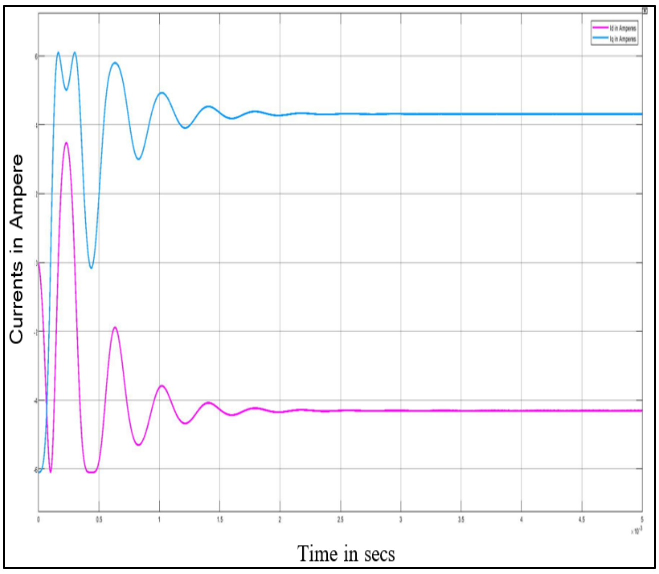

Figure 8. dq Currents Output

The simulation of the VSC system gives useful information about its performance and efficiency. The output voltage waveform is balanced three-phase AC with a sinusoidal waveform. The amplitude and frequency of the voltages is as per the desired output is evident from Figure 8, which reflects effective modulation of AC output from DC input. The current is as per the voltages, balanced and sinusoidal is evident from Figure 6. The amplitude is as per the requirement of the load, and the harmonics are filtered out by the LCL filter, reflecting effective filtering and control. The currents on the dq axis are important while considering the control strategy. The id component generally controls active power, and the iq component controls reactive power. The current follows its reference value precisely, reflecting that the active power control loop is working properly is evident from Figure 8.

6. Conclusion

The mathematical modelling and simulation of the VSC with a DC voltage source of 800 V and an inverter rating of 5 kVA have been successfully achieved. The aim of this research was to develop a complete picture of VSC operation, including key features such as an LCL filter, PWM, dq current control, voltage control methods, and a PI controller for monitoring key outputs. Utilizing VSCs in virtual inertia control methods based on the Virtual Synchronous Generators (VSGs) concept is a cutting-edge solution for ensuring grid stability and integrating renewable energy sources. The results achieved and the learning developed provide a solid foundation for further research and development in VSC technology.

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