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Electromagnetic Transient Studies

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**Comparison of different photovoltaic park models for
electromagnetic transient studies**

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Département de génie électrique

Mémoire présenté en vue de l'obtention du diplôme de Maîtrise ès sciences appliquées

Génie électrique

Décembre 2023

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Ce mémoire intitulé:

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electromagnetic transient studies**

présenté par **Hossein HOOSHMANDISAF**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DEDICATION

To my wife and my parents

ACKNOWLEDGEMENTS

I would like to express my sincere and deep gratitude to my supervisor Professor Jean Mahseredjian. Completion of this thesis would not have been possible without his invaluable expertise in the topic, continuous support, and excellent guidance. Working under his supervision is a privilege for me which provided me the opportunity to broaden my technical knowledge.

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RÉSUMÉ

Les énergies renouvelables ont récemment retenu plus d'attention et ont été considérablement développées et installées en raison du réchauffement climatique et de l'inquiétude internationale pour les combustibles fossiles traditionnels. Étant donné que la stabilité des réseaux électriques peut être affectée par une forte pénétration des centrales photovoltaïques connectées au réseau, le développement de modèles précis et efficaces joue un rôle important dans la caractérisation du comportement du système électrique. De plus, afin d'étudier l'interaction des parcs photovoltaïques (PV) avec le réseau, les simulations de transitoires électromagnétiques (EMT) sont nécessaires.

L'objectif de ce projet de recherche est d'examiner de manière exhaustive les différents modèles de PV pour la simulation des EMT. Les systèmes solaires photovoltaïques sont basés sur des onduleurs. Par conséquent, une comparaison des différents modèles d'onduleurs utilisés dans les parcs photovoltaïques tels que le modèle détaillé, le modèle de valeur moyenne et le modèle de fonction de commutation est présentée. De plus, ces modèles sont comparés en termes de précision et de charge de calcul.

En outre, cette thèse présente des comparaisons complètes des modèles de parcs photovoltaïques et de leurs performances à l'aide d'un système de référence. Enfin, les différences entre les différents modèles de parcs photovoltaïques et le modèle approprié pour chaque objectif de simulation sont discutés.

ABSTRACT

Renewable energy has recently absorbed more attention and has been considerably expanded and installed due to global warming and international concern for traditional fossil fuel. Since stability of power grids can be affected by high penetration of grid-connected photovoltaic (PV) power plant, developing accurate and efficient models has an important role in characterization of power system behavior. Moreover, in order to study the interaction of PV parks with the network, accurate electromagnetic (EMT) simulations are required.

The objective of this research project is to comprehensively review the different PV park models for the EMTs simulation. The solar PV systems are based on inverters. Therefore, a comparison on the different inverter models used in PV parks such as detailed model, average value model and switching function model is presented. Moreover, these models are compared in terms of accuracy and computational burden.

Furthermore, this thesis presents comprehensive comparisons of PV park models and their performance using a benchmark system. Finally, the differences of different PV park models and the suitable model for each simulation purpose are discussed.

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LIST OF SYMBOLS AND ABBREVIATIONS

EMTP	Electromagnetic Transient Program
EMT	Electromagnetic Transient
AC	Alternating Current
DC	Direct Current
PV	Photovoltaic
PVP	Photovoltaic Park
PVPC	Photovoltaic Park Control
GSC	Grid Side Converter
DM	Detailed Model
AVM	Average Value Model
SFM	Switching Function Model
WECC	Western Electricity Coordinating Council
FRT	Fault Ride Through
DSC	Decoupled Sequence Control
PWM	pulse width-modulated
REGC	Renewable Energy Generator Converter
REEC	Renewable Energy Electrical Controls
REPC	Renewable Energy Plant Control

CHAPTER 1 INTRODUCTION

1.1 Context and motivation

Due to global warming and international concerns on usage of traditional fossil fuel power plants, installation and commissioning of renewable energy sources has been on the rise during the last decades. It is acknowledged that the security and stability of power grids can be affected by the high penetration of grid-connected renewable energy sources such as photovoltaic (PV) and wind parks [1]. Since power system studies intensely depend on the simulation tools, developing accurate and efficient models has an essential role in the characterization of the power system's behavior [2].

Analysis of electromagnetic transients (EMTs) in modern power systems relies on accurate models of the system's components, PV parks (PVP) among them, within a wide frequency range. The detailed model (DM) representation of PVP is the most accurate method for EMTs studies. A standard PVP consists of PV modules, the DC-DC and DC-AC converters and their controllers, the collector network, and the PVP plant controller. A main drawback of detailed modeling of PVP is the requirement of a small integration time step which results in long computational times and necessitates significant computational resources. This issue is overcome by making simplifications to the DM, such as averaging dynamics. Furthermore, it is imperative to assess which simplified PVP models can be used for different EMT studies.

Summarizing, the penetration of PV power plants is increasing in power systems, and it is essential to develop accurate models with good computational performance to analyze their interaction with large scale traditional power grids [3].

1.2 Objectives

The objectives of this research project are:

- To provide a comprehensive review of different PVP models for EMT simulation.
- To present a comprehensive comparison of the existing PVP models and their performance, in terms of accuracy and computational resources, using the DM as benchmark.

- To clarify the differences between different PVP models and discuss the suitable model for different studies.

1.3 Thesis Outline

This thesis is organized as follow:

In Chapter 2, previous research conducted on PVP modeling for the EMT simulations is presented. In Chapter 3, the switching function model (SFM) of the voltage-sourced converter is presented. Then, PV inverter control system is discussed in Chapter 4. The simulation results are presented in Chapter 5, where the SFM results considering both normal operation mode and blocked mode are compared with the DM and average value model (AVM). In Chapter 6, the western electricity coordinating council (WECC) model is described. Then, its different modules simulation results are compared with the DM, AVM, and SFM results. Finally, Chapter 7 summarizes the result achieved in Chapter 5 and Chapter 6 and suggests the appropriate model for each type of EMT study. Finally, conclusions and recommendations for future work are given.

CHAPTER 2 PVP MODELING FOR EMT ANALYSIS

2.1 PVP configuration and its main equipment

A lot of equipment is used in a PV system, and new developments appear on the market regularly. A traditional PVP consists of PV modules, DC/DC converters, and DC/AC converters along with their control systems. The existing and new technologies of each type of equipment are reviewed in this chapter.

Figure 2-1 shows the PVP configuration used in EMTP [4]. It includes PV modules, a voltage-sourced converter (VSC) and a resistive DC-chopper used for DC bus overvoltage protection. Also, to improve the power quality, it uses a line inductor and an AC harmonic filter at the grid side converter (GSC).

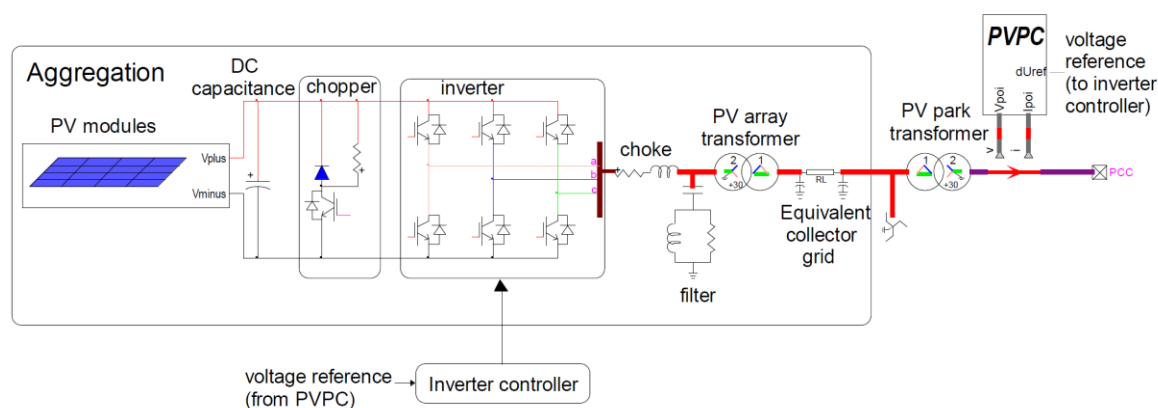


Figure 2-1 PVP configuration used in EMTP [4]

2.1.1 PV module

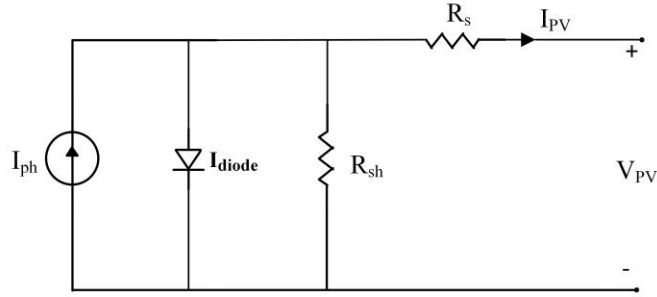


Figure 2-2 Equivalent circuit of a PV array [5]

Figure 2-2 shows the equivalent electrical circuit of the PV module. Using this equivalent circuit, the V-I characteristics of the PV can be derived, noting that the diode exhibits a nonlinear behavior [6].

The relation between I_{pv} and V_{pv} in Figure 2-2 is given by [7]:

$$I_{pv} = I_{ph} - I_{diode} - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (2-1)$$

where I_{diode} is the current flowing through the diode, as given by (2-2), R_s is the series resistance and R_{sh} is the shunt resistance. The diode parameters can be calculated using the standard conditions data (i.e., irradiance of 1000 W/m^2 and temperature of 25°C).

$$I_{diode} = I_0 \left[\exp\left(\frac{V_{diode}}{aV_{th}}\right) - 1 \right] \quad (2-2)$$

Where

$$V_{diode} = \frac{V_{pv} + I_{pv}R_s}{N_s} \quad (2-3)$$

In (2-3), N_s represents the number of cells connected in series in the module.

The diode thermal voltage is given by:

$$V_{th} = \frac{kT_{ref}}{q} \quad (2-4)$$

Where k is the Boltzmann's constant, q the charge of an electron and T_{ref} the reference temperature in Kelvin.

Also in (2-2), I_o represents the diode saturation current, given by:

$$I_o = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{\alpha N_s V_{th}}\right) - 1} \quad (2-5)$$

Substituting (2-5) into (2-1) results in:

$$I_{pv} = I_{ph} - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} - I_o \left[\exp\left(\frac{V_{pv} + I_{pv} R_s}{\alpha N_s V_{th}}\right) - 1 \right] \quad (2-6)$$

For time domain simulations, the nonlinear expression (2-6) is resolved to obtain either a Norton or a Thevenin equivalent of the PV module. A simple procedure is to evaluate (2-6) for maximum power point (MPP) operation and to consider the derivative of the power with respect to V_{pv} equal to zero. The resultant two expressions are iteratively solved, for example using the Newton-Raphson method, to provide such Norton/Thevenin equivalent [8].

To consider the irradiance and temperature as input parameters, a two-diode PV cell model is proposed in [9]. However, that model is not suitable for conventional EMT simulations [10]. A two-diode model, based on the weather conditions, is proposed in [11]; such model is more appropriate for general applications than the one in [8]. Also, a model with three diodes, which includes the impact of electrical characteristics, is developed in [12]. It should be mentioned that irradiance changes slowly and it takes few minutes for a cloud to fully cover the PV panels. Hence, irradiation can be considered quasi-static, leading to the adoption of the single diode model in EMTP.

For the characterization of PV modules under partial shading conditions, a model is proposed in [5] with specific application of maximum power tracking (MPT). It should be mentioned at this point that, in the aggregated model used in EMTP, partial shading can only be considered by simplifying it to a lower irradiation value. However, that is not a realistic representation, since under partial shading conditions some converters in the park have low power output, while others have high power output.

2.1.2 DC-DC Converter

Although using DC-DC converters in PV systems is not mandatory, they can be used to regulate the output DC voltage. Typically, the DC-DC converter is controlled to extract the maximum power from the panel using MPT methods. Different types of DC-DC converter topologies can be used for power conversions, such as buck converter [13-18], boost converter [19-23], buck-boost converter [24-29], cuk converter [30, 31], SEPIC [32-35], and flyback converter [36-40]. According to the type of application, the appropriateness of the converter varies. The PV model employed in EMTP does not incorporate a DC-DC converter.

2.1.3 Voltage-Sourced Converters

2.1.3.1 Two-level converters

In PV systems, the transformation from DC to AC of the absorbed solar power is accomplished by a VSC. Several configurations have been presented for VSCs, such as two-level, multi-level, and H-bridge, among others. [41]. The two-level VSC topology, adopted in EMTP, is illustrated in Figure 2-3. It consists of three branches connecting each phase to the DC side. Two IGBT switches in each branch are switched using the gate signals generated by a Pulse Width Modulation (PWM) scheme or by a space-vector modulation (SVM) strategy. In the PWM method, modulating voltages are produced by the control schemes. These modulating voltages are compared with a carrier signal. The outputs of the PWM scheme are the gate pulses.

The output voltage of the VSC consists of a fundamental component, as well as multiple high-frequency components that need to be suppressed by a low-pass filter. Regardless of the switching strategy employed, such as PWM or SVM, the amplitude and phase angle of the fundamental

component can be controlled during the modulation process. However, the maximum achievable amplitude is limited to a fraction of the DC-link voltage. For instance, in carrier-based sinusoidal PWM (SPWM), the maximum attainable amplitude is typically limited to 0.5 (half of the DC-link voltage). In carrier-based SPWM with third-harmonic injection, as well as in SVM, the maximum achievable amplitude is 0.577 (0.577 times the DC-link voltage) [42].

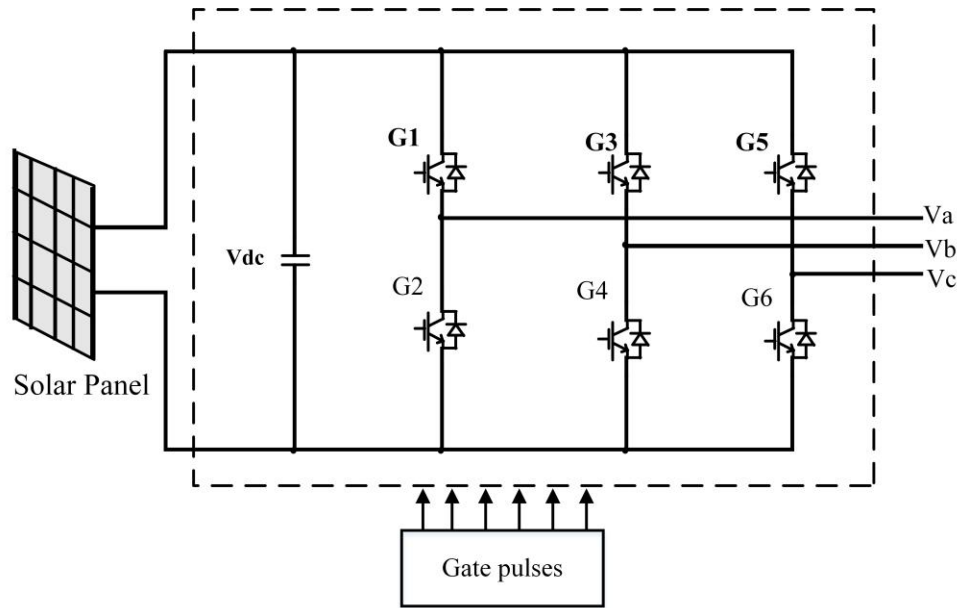


Figure 2-3 Two-level VSC [41]

2.1.3.2 Multi-level converters

By the end of the 1980s, multi-level converters, which consist of several modules with smaller ratings, were extensively researched as a solution to further improve the performance of two-level converters [43]. Multi-level converters reduce power losses, harmonic content, and semiconductor switching stress (dv/dt and di/dt) [44, 45]. They can operate at low switching frequencies and can increase voltage ratings by applying a smaller voltage across semiconductor devices. However, they have a more complex structure, resulting in a larger footprint. Also, their modulation and control are more complex. Furthermore, compared to two-level converters, they incur in higher investment cost due to a larger number of components. In recent years, application of the multi-level converters in EMT simulations are studied in [46-50].

2.1.4 Low-Pass Filter

To connect the VSC to the grid, a three-phase low-pass filter is necessary. It serves two main purposes: adding impedance to the VSC's AC-side terminals and attenuating harmonic components of the VSC's AC-side voltage, thus preventing their penetration into the grid. There are various types of filters, but the low-pass LC filter is commonly used in PV systems due to its simplicity and cost-effectiveness.

The LC filter consists of capacitors and inductors, and the three capacitors can be arranged in either Y-configuration or Δ -configuration. However, the Y-configuration is typically preferred because it is more convenient for analysis and evaluation of the filter's performance.

The effectiveness of the filter used in the PV system is influenced by various factors, including the equivalent inductance of the grid as perceived by the system. The primary objective is to limit the harmonic currents injected by the PV system into the grid to maintain them at acceptable levels. By achieving this objective, voltage distortion at the Point of Common Coupling (PCC) is also minimized. To attain this, appropriate values for the filter inductance and capacitance are chosen.

Typically, the selected inductance value falls within the range of 0.1 to 0.25 per unit (p.u.) [42]. This choice is made to keep the size and cost of the reactor (inductor) low. If an estimate of the grid equivalent inductance is available, it can be used to calculate the desired value for the inductance. This calculation ensures that the resonant frequency of the LC filter tank circuit, which comprises the parallel connection of 1) grid equivalent inductance plus the interconnection transformer leakage inductance, 2) capacitor, and 3) inductance, is significantly higher than the grid's nominal frequency. However, it should still be considerably lower than the VSC switching frequency. This highlights the advantage of having a higher switching frequency for the VSC in terms of filter design. A higher switching frequency allows for a smaller filter capacitance requirement. Nevertheless, the choice of the switching frequency is constrained by VSC efficiency considerations and is typically set below 6 kHz for most high-power electronic converter systems.

2.1.5 Interconnection Transformer

A built-in transformer is commonly included in a grid-connected PV system to adapt the VSC AC-side terminal voltage to the nominal PCC voltage. The transformer, referred to as the isolation

transformer, typically has a Δ -winding connection on one side. This permits to avoid triplet harmonics going into the AC-side. Moreover, the transformer isolates the PV system from the grid, in terms of zero-sequence components due to fault currents.

2.2 Review on PV modeling for EMT simulation

Each technological development in the field of PV systems has pushed research to produce more accurate and/or numerically efficient PV models. In this section, the DM and AVM of the VSC, considered one of the most important components of PV Parks, are reviewed; the SFM is relegated to Chapter 3 due to the number of details presented.

2.2.1 Voltage-sourced converter modeling

2.2.1.1 Detailed Model (DM)

The DM of a VSC considers various parameters that impact the VSC's operation; these include input and output voltages, switching frequency, and circuit inductance and capacitance. When simulating a three-phase VSC for EMT analysis, the following can be outlined:

2.2.1.1.1 Switching model and power semiconductor devices

In practice, the switches employed within the Voltage Source Inverter (VSC) are power semiconductor devices such as MOSFETs or IGBTs. The switches are internally modeled as ideal switches with a non-linear diode which requires an iterative solution scheme to find the correct operating point. Note that this can impose a considerable computational burden, leading to long computation times.

2.2.1.1.2 DC-link capacitor

The DC-link capacitor plays a vital role in the VSC by smoothing out the DC voltage and providing a stable voltage source for the inverter. Its behavior is represented using an equivalent circuit that includes the capacitance value and the equivalent series resistance (ESR).

2.2.1.1.3 Control strategy

The selection of a control strategy is another crucial aspect of VSC modeling. The control strategy determines the VSC's operation and its response to changes in input and output voltages. PPWM is the most widely used control strategy for VSCs. PWM control can be implemented through various techniques, including:

Carrier-based PWM: This technique generates a high-frequency carrier waveform that is modulated by a lower frequency signal. The modulated waveform is then compared to a reference waveform to generate the switching signal for the VSC.

Space vector PWM: In this approach, the three-phase voltage and current signals are transformed into a two-dimensional space vector. The space vector is then modulated to generate the switching signals for the VSC.

Figure 2-4 depicts the DM of a VSC. It consists of a two-level VSC block and a PWM block. Figure 2-5a shows the converter circuit for the two-level VSC. The electronic valve, as shown in Figure 2-5b consists of an IGBT, modeled by two non-ideal diodes, an off-state resistance, and a snubber circuit. Each diode is modeled by a nonlinear resistance. Note that this simplified model of an IGBT can represent conduction losses in an accurate way if the nonlinear resistance is selected according to IGBT datasheets. The modeling of the switching transient, on the other hand, is much more complex. The RLC circuit in the IGBT of Figure 2-5b, can potentially emulate switching transient effects, such as over voltages and ringing during the switching transient. However, tuning the RLC circuit to specific values is challenging. Also, the EMTP diagram of the PWM block is presented in Figure 2-6.

The time step required for the DM is determined by the PWM frequency and the desired level of detail during the IGBT switching transients. In this case the timestep typically needs to be smaller than $20\mu\text{s}$.

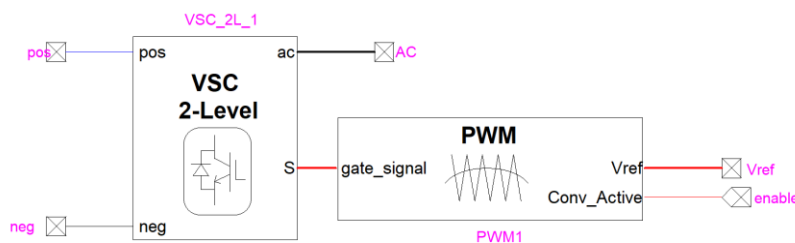


Figure 2-4 Detailed model of VSC with PWM

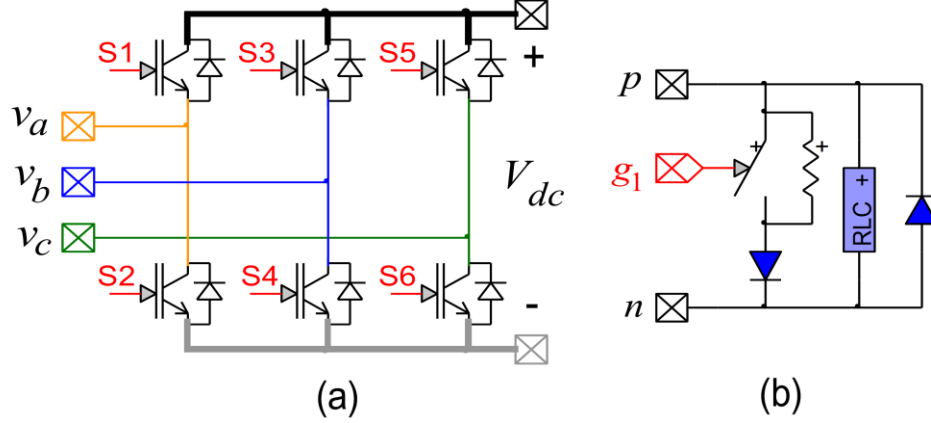


Figure 2-5 (a) Two-level Converter, (b) IGBT valve

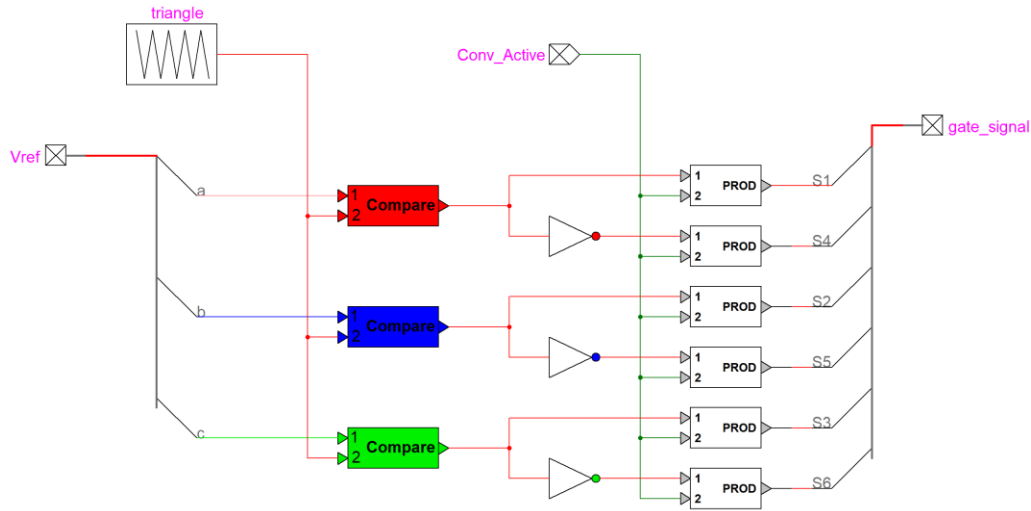


Figure 2-6 PWM control block

2.2.1.2 Average Value Model (AVM)

As mentioned in the previous section, the DM of switching converters impose a small time step and, consequently, more computational effort, which in turn reduces the number of switching converters that can be modeled in a large-scale power system. This is especially challenging in a grid with a high level of penetration of inverter-based power generation [51]. To overcome this issue, dynamic AVMs have been proposed for different converters such as AC-DC [52-56], DC-DC [57-62], and DC-AC converters [49, 63-67]. Based on the methodology used to obtain the

relationships among the variables, there are two types of AVM, analytical AVMs [52, 55, 56] and parametric AVMs [68-73]. In AVMs, the current and voltage variables are approximated by their corresponding dynamic average values, and the high-frequency switching is neglected. This permits to use a large time step that renders AVMs as more efficient, computationally speaking, than DM [51].

Given the conventional operation of PWM and VSC, along with a three-wire three-phase AC connection, it is possible to establish an algebraic relationship between the average values of the AC and DC variables. This relationship can be derived using an orthogonal reference frame, such as the $\alpha\beta$ frame or a dq frame, and by applying the principle of energy conservation.

The AVM is presented in Figure 2-7. On the AC side, the AVM employs three controllable voltage sources, as shown in Figure 2-7, to replicate the calculated average values of the three-phase AC-side terminal voltage v_a, v_b , and v_c . Meanwhile, the three-phase current i_a, i_b , and i_c serves as another output of the AVM and is determined by the AC circuit connected to the terminals of the VSC. The DC and AC voltage and current variables are related by (2-8) and (2-9). It is assumed that the input v_{dc} is available from the circuit model of the DC-link capacitor, thereby making i_{dc} an output that can be generated by a controllable current source.

$$v_{dc} i_{dc} = v_a i_a + v_b i_b + v_c i_c \quad (2-8)$$

$$i_{dc} = \frac{v_a i_a + v_b i_b + v_c i_c}{v_{dc}} \quad (2-9)$$

Also, the AVM of the VSC shown in Figure 2-7 assumes the utilization of a dq -frame control strategy. In this model, the variables m_d and m_q represent the d - and q -axis components of the PWM modulating waveforms (m_a, m_b , and m_c). These components are obtained from the real- and reactive-power control scheme. The amplification gain of the VSC, denoted as k_{dc} , is dependent on the specific type of PWM employed. The reference angle ρ , commonly selected as the grid voltage angle, plays a significant role.

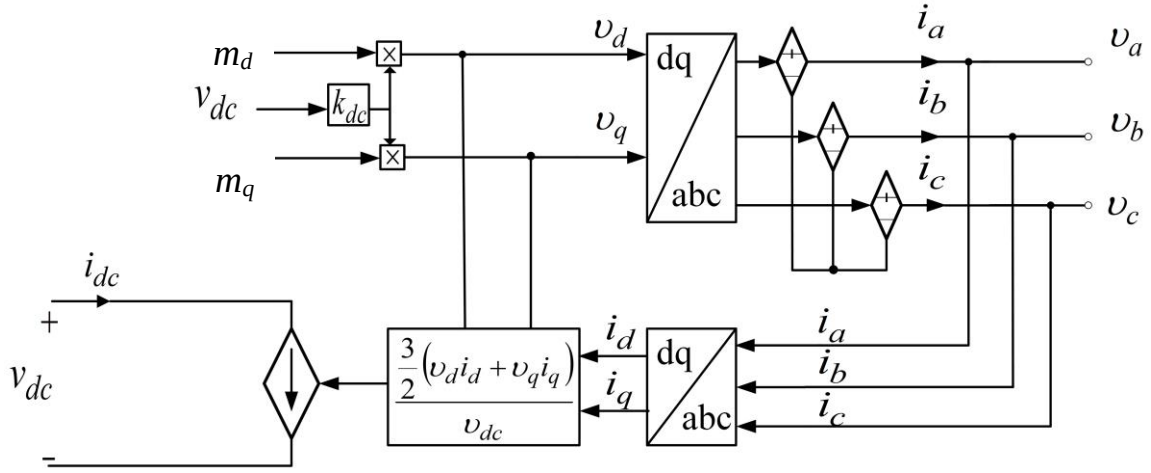


Figure 2-7 Average value model of the VSC [42]

The synchronization scheme of the PV system, such as a phase-locked loop (PLL), provides the reference angle ρ . It is important to note that the rate of change of ρ ($\frac{d\rho}{dt}$) represents the dynamic operating frequency of the PV system, which ultimately reaches a steady-state value equal to the grid frequency ω_0 .

If a topological model of the VSC is utilized instead of the AVM, it may be necessary to perform a dq -to- abc frame transformation to derive the PWM modulating waveforms (m_a, m_b and m_c) from the d - and q -axis components (m_d and m_q).

The equations (2-8) and (2-9) establish a power balance between the power entering the VSC DC-side (P_{dc}) and the power leaving the VSC AC-side terminals (P_t), although they ignore the VSC power losses. Since the VSC is commonly controlled in either a dq frame or the $\alpha\beta$ frame, the dq -frame or $\alpha\beta$ -frame equivalents of (2-9) are often more convenient to use in the AVM. Thus, using an approach similar to [48], the ideal controlled voltage sources can be expressed as:

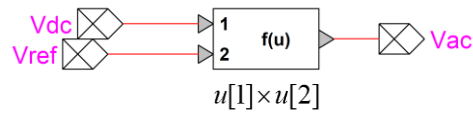
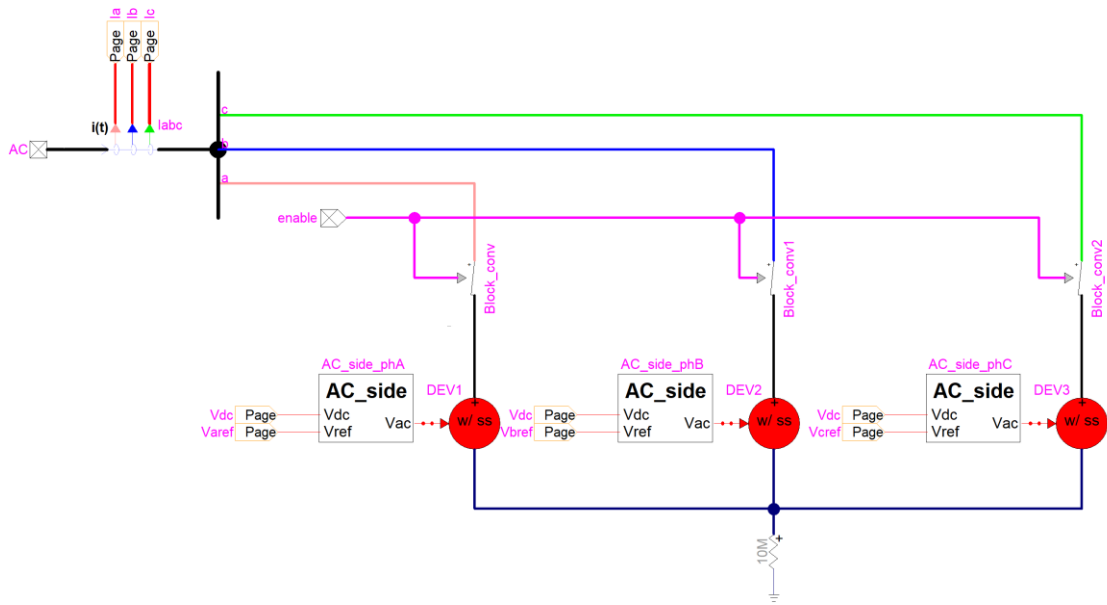
$$\begin{aligned} U_{va} &= \frac{1}{2} V_{ref_a} V_{dc} \\ U_{vb} &= \frac{1}{2} V_{ref_b} V_{dc} \\ U_{vc} &= \frac{1}{2} V_{ref_c} V_{dc} \end{aligned} \quad (2-10)$$

Using the power balance at the AC and DC sides and neglecting converter's losses the current source value is given by:

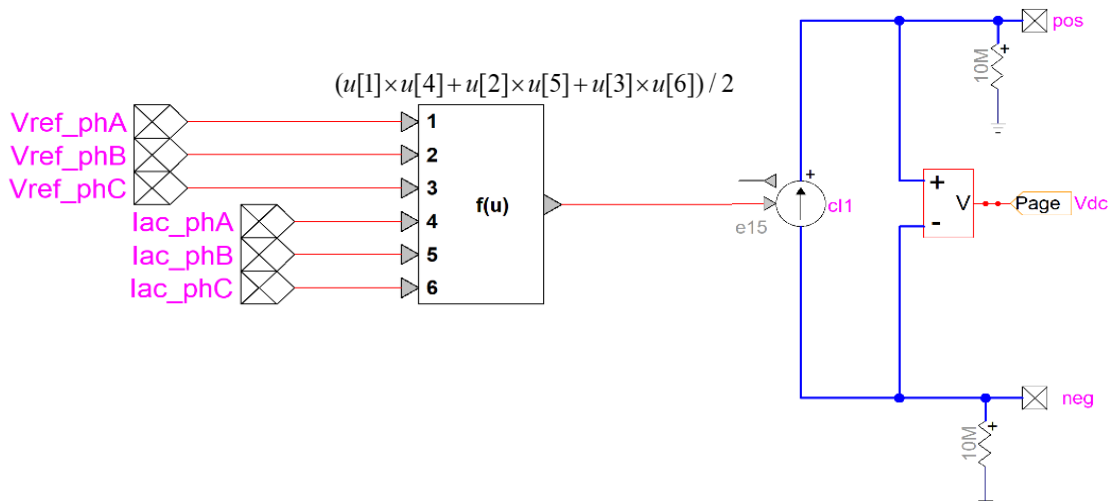
$$I_{DC} = \frac{1}{2}(V_{ref_a} i_a + V_{ref_b} i_b + V_{ref_c} i_c) \quad (2-11)$$

The main disadvantage of AVMs is that it does not account for high-frequency voltage/current waveform distortion by the VSC, nor their impact on the grid and controls. Moreover, AVMs are valid only for frequencies up to about one-third of the VSC switching frequency, accounting that the VSC operates in the linear modulation region, that is, if $\sqrt{m_d^2 + m_q^2} \leq 1$ [42].

Figure 2-8 shows the AVM of the VSC as implemented in EMTP, in which both AC- and DC-side are physically decoupled. The influence of the AC current on the DC bus is modeled by a controlled current source, whereas the influence of the DC voltage on the AC voltage is modeled by a controlled voltage source.



(a)



(b)

Figure 2-8 AVM of VSC a) AC side b) DC side

2.2.2 Aggregated models

A PVP usually contains hundreds of PV units. Modeling of all individual PV units imposes a computational burden for system level studies and controller design. To reduce simulation time, equivalent models are used to mimic the dynamic performances of PVP. The equivalent models of PVP can be classified as steady-state and transient equivalent models. The former is used for power flow and static stability analysis [74, 75], and the latter is used for the transient analysis. For transient equivalent models, there are two possibilities: the single-machine equivalent model and the multi-machine equivalent models [76]. In single machine type, all PV units are aggregated in one unit [77].

The single-machine equivalent model can produce significant errors when individual PV units have different fault ride through (FRT) behavior [78]. Two common methods for this type of aggregation are the capacity equal weighted method and the parameter identification method [79]. To overcome the mentioned drawback of the single-machine equivalent model and improve accuracy, the PV units can be divided into different clusters. In this method, the PV units within a cluster have the same characteristics, while different clusters could have differences [80-83]. The four steps used to constructing the multi-machine equivalent model of PV are: grouping of PV units, accumulating PV units within a group, assigning the collector network, and validating the model [84].

The most common methods for the calculation of aggregated PV parks are: the weighting method [85, 86], the substitution method [87], and the optimization method [79, 88]. As for the equivalent network of the collector system, the most commonly used techniques are: voltage deviation method [89, 90], current injection method [82], power loss method [91], and circuit transformation method [92, 93]. The current injection technique is the most accurate and computationally efficient [84].

In EMTP, the aggregation process encompasses PV panels, the collector grid, the model of HV/MV PV substation including overvoltage protection, overcurrent, and differential current protections, measuring current and voltage transformers. Therefore, in the aggregated park-level model, all the separate sub-systems are condensed into a single equivalent park-level component. As a result, there are fewer components, leading to improved EMT simulation performance. This approach is commonly employed for grid-level analysis. When it comes to converter models such as DM,

AVM, and SFM, there is a uniformity in their application, whether employed in a detailed or aggregated model.

CHAPTER 3 SWITCHING FUNCTION MODEL (SFM)

3.1 Introduction

The conventional method used to establish the mathematical model of a power electronic converter typically involves analyzing its modes or states. Due to its switching nature, the circuit undergoes changes in its state configurations, which are referred to as modes. A set of differential equations is derived to describe the circuit in each mode. The interconnection between these modes is usually determined by a variable, such as voltage, current, or both. These equations are solved for each state and then interconnected, where the final value of a variable in one mode becomes the initial value in the next mode. This process is repeated until the final simulation time is reached.

As an alternative, the switching function technique represents the on and off states of a semiconductor switch by a signal, denoted as $F(t)$, that takes the values of 0 and 1 (unipolar scheme) or the values of ± 1 (bipolar scheme).

The SFM has been used for the modeling of different types of converters [94-101]. A SFM for the voltage-source inverter (VSI) is studied in [96], and improved for the use in PWM AC–DC rectifiers and the PWM AC–DC–AC converters. A rapid diagnostic technique has been suggested in [95] to identify open-switch faults in inverters without the need for sensors, aiming to enhance the dependability of power electronic systems. The approach outlined in [95] involves analyzing the switching function model of the inverter under normal and faulty scenarios. By scrutinizing the collector-emitter voltages of the lower power switches in each leg, open-circuit faults can be identified, given the diverse voltages experienced by these switches under healthy conditions compared to open-switch fault conditions in certain instances.

A switching function-based method has been proposed in [99], to establish a multiscale model for DC/DC converters, allowing the analytical solutions of the state variables to be obtained at both circuit and device-level scales. In [98], an improved cascaded multi-level inverter is proposed to minimize the leakage current and reduce the switching and conduction losses in PV systems. The switching function concept is used in [98] to analyze the PV terminal and common-mode voltages of the proposed configuration.

Existing research has predominantly concentrated on device-level studies, highlighting a significant void in exploring the advantages of employing the switching function method within power systems. This gap is particularly conspicuous in systems characterized by a high penetration of PV systems.

3.1.1 Definition of the unipolar switching function

The switching function is a signal that, when multiplied by the input voltage (or current), yields the output voltage (or current). Consider the simple circuit depicted in Figure 3-1, where a voltage source, $V(t)$, is connected to the left-hand side (LHS) of the semiconductor switch. When the switch is closed during the time interval $t_1 - t_2$, the output voltage on the right side of the switch assumes the same value of $V(t)$. Conversely, when the switch is open in the time interval $t_2 - t_3$, the output voltage becomes zero. By assigning the logic value of 1 to the closed switch state and the logic value of 0 to the open switch state, $F(t)$ can be defined as follows and it is illustrated in Figure 3-2:

$$F(t) = 1 \text{ switch closed for } t_1 < t < t_2 \text{ and } V_{AB}(t) = V(t)$$

$$F(t) = 0 \text{ switch open for } t_2 < t < t_3 \text{ and } V_{AB}(t) = 0$$

The period of $F(t)$ is $t_3 - t_1$ and the switching frequency, f_s , is $f_s = \frac{1}{t_3 - t_1}$. The term "unipolar" is used as $F(t)$ assumes positive values only. This unipolar switching function captures the fundamental repetitive behavior of the semiconductor switch.

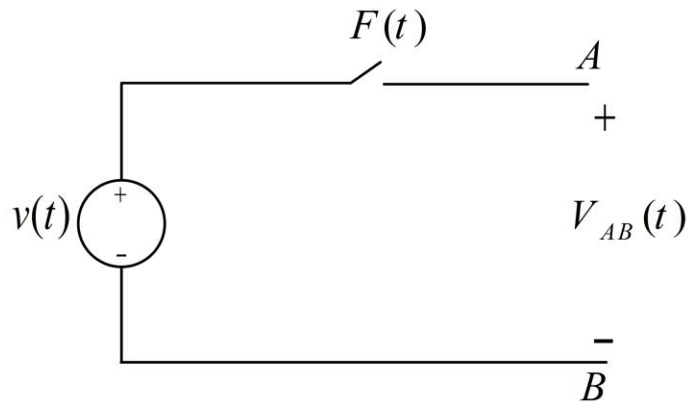


Figure 3-1 Definition of the switching function

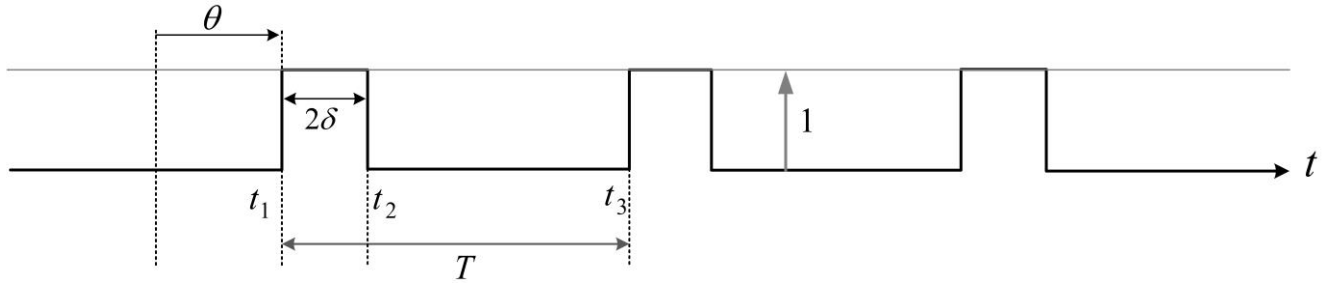


Figure 3-2 The basic switching function [102]

3.1.2 The bipolar switching function – bridge configuration

In a bridge configuration, as shown in Figure 3-3, the operation of the switches is as follows [102]: S_1 is paired with S_4 , and S_2 is paired with S_3 . Each pair operates in an anti-parallel manner, meaning they never overlap in their on/off states. However, there may be periods where both switches in a pair are off, resulting in dead periods. Each pair is controlled by a unipolar switching function: S_1 and S_4 are controlled by $F_{14}(t)$, while S_2 and S_3 are controlled by $F_{23}(t)$. These two unipolar switching functions have the same pulse width but are phase-shifted by 180 degrees.

To establish the relationship between the input and output voltages, the modes of the circuit need to be derived. When the switching function $F_{14}(t)$ is in state 1, switches S_1 and S_4 are turned on. In this case, the output voltage $V_{CD}(t)$ is determined by multiplying $F_{14}(t)$ with the input voltage $V_{AB}(t)$. This contribution of Mode I to the output voltage is illustrated in Figure 3-4(a).

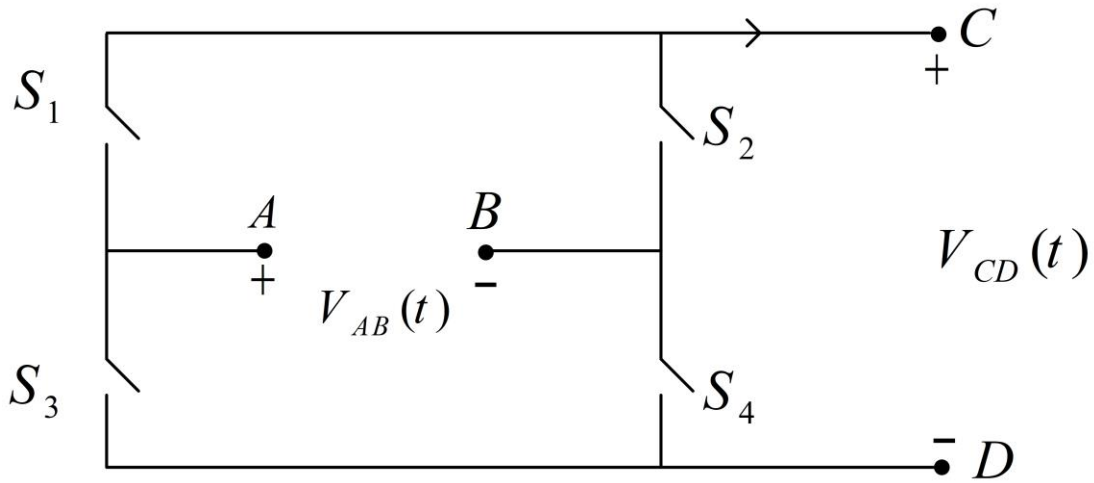


Figure 3-3 The circuit diagram of the bridge configuration

Similarly, when the switching function $F_{23}(t)$ is in state 1, switches S_2 and S_3 are turned on. The output voltage in this scenario is given by the expression: $V_{CD}(t) = -F_{23}(t)V_{AB}(t)$

Then the output is reversed. This corresponds to the impact of mode II on the output voltage, as illustrated in Figure 3-4(b). Additionally, there exists mode III in which none of the four switches are active, as depicted in Figure 3-4(c). During this mode, none of the switches are turned on, and both switching functions remain in the zero state. $F_{23}(t) = -F_{14}(t) = 0$

The output voltage is null, indicating the absence of any contribution from mode III towards the output voltage. $V_{CD}(t) = 0$

The Superposition theorem is applicable in this case, and the voltage waveform $V_{CD}(t)$ is determined by the combined contributions of modes I and II. Mode III, however, does not have any impact on the waveform. Therefore, the reflection of $V_{AB}(t)$ on the DC terminals, $V_{CD}(t)$, can be expressed as follows:

$$\begin{aligned} V_{CD} &= F_1(t) V_{AB} - F_2(t) V_{AB}(t) \\ V_{CD} &= [F_1(t) - F_2(t)] V_{AB}(t), \end{aligned}$$

and

$$V_{CD} = F_B(t) V_{AB}(t),$$

where

$$F_B(t) = [F_1(t) - F_2(t)],$$

$V_{AB}(t)$ is the input voltage, $V_{in}(t)$; $V_{CD}(t)$ is the output voltage, $V_o(t)$. Hence for the bridge configuration

$$V_o(t) = F_B(t) V_{in}(t) \quad (3-1)$$

The switching function $F_B(t)$ is relating the input voltage $V_{in}(t)$ to the output voltage $V_o(t)$ in a switched circuit. These expressions represent an amplitude modulation where the switching function is acting on the input voltage to give the output voltage.

For a three-phase system, another leg is added to the ones in Figure 3-3 to have two other input voltage ($V_{BC}(t)$ and $V_{CD}(t)$). Similar to Figure 3-2, the output voltage can be calculated using the superposition theorem.

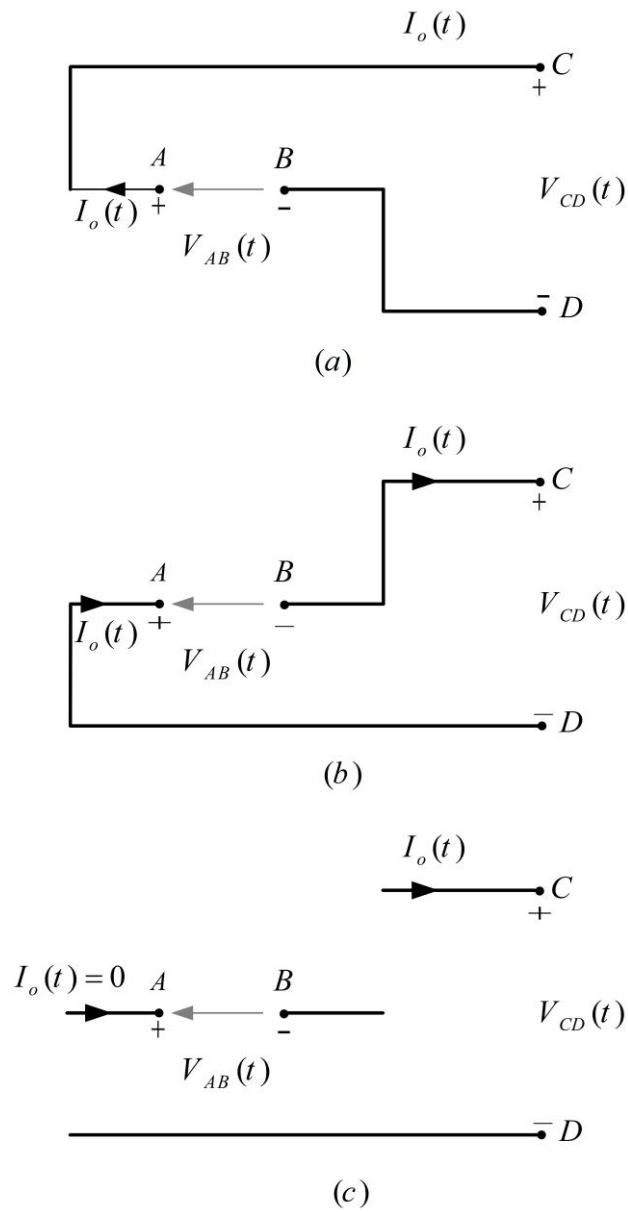


Figure 3-4 Bridge configuration: (a) Mode I, (b) Mode II and (c) Mode III

3.2 Switching function model in EMT analysis

Using the SFM, high-frequency dynamics imposed by semiconductor switches on the system can be modeled without modeling the semiconductors themselves. This allows us to analyze the grid implications of power electronic converter switching while neglecting converter internal details.

Based on the operation mode, the DC-side and AC-side variables can be defined as an input or output. Then, for defining the task to be accomplished by the converter, the transfer function is achieved ((3-2), and (3-3)) [100].

Based on the transfer function theory, in the VSC, the input current (I_{in}) and output voltage (V_{an}, V_{bn}, V_{cn}) are the dependent variables while the input voltage (V_d) and output current (I_a, I_b, I_c) are the independent variables. Therefore, the relationship between the input and output variables can be expressed as [96]:

$$[V_{an}, V_{bn}, V_{cn}] = TF_1 V_d \quad (3-2)$$

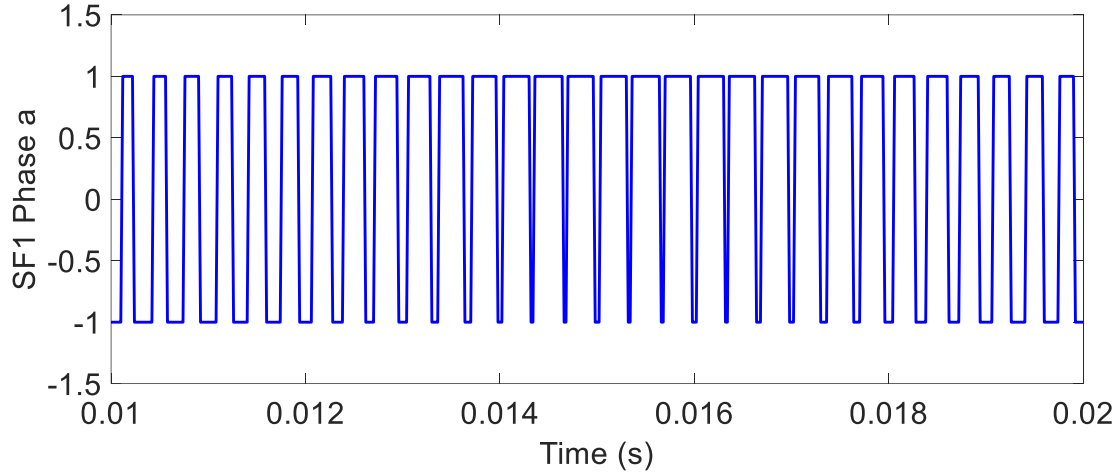
$$I_{in} = TF_2 [I_a, I_b, I_c]^T \quad (3-3)$$

where V_{an}, V_{bn} , and V_{cn} are the phase voltage, V_d is the DC voltage, and TF is the transfer function of the VSC. Generally, the transfer function consists of the several switching functions:

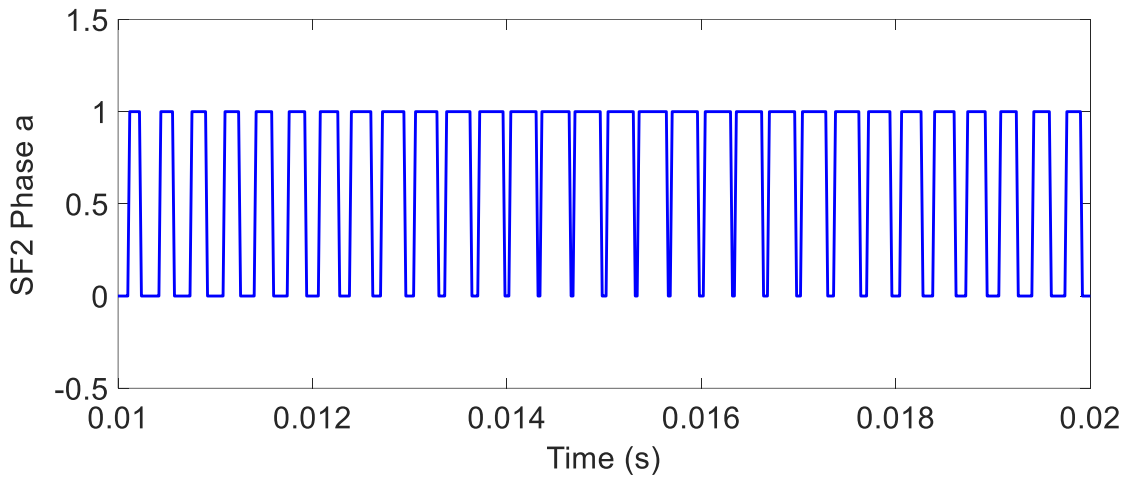
$$TF_1 = [SF_{1a}, SF_{1b}, SF_{1c}], \quad (3-4)$$

where SF_{1a}, SF_{1b} , and SF_{1c} are the switching function of phases a , b , and c , respectively.

A control strategy commonly used to define the switching functions is the sinusoidal PWM (SPWM) technique. If the reference voltage is equal to or greater than the triangular carrier signal, the SF value is equal to one. Otherwise, the SF is equal to zero. Based on the SPWM, the switching functions SF_{1a} and SF_{2a} illustrated in Figure 3-5 are achieved for phase a ; for phases c and b , a 120 and -120 phase shift, respectively, is considered.



(a)

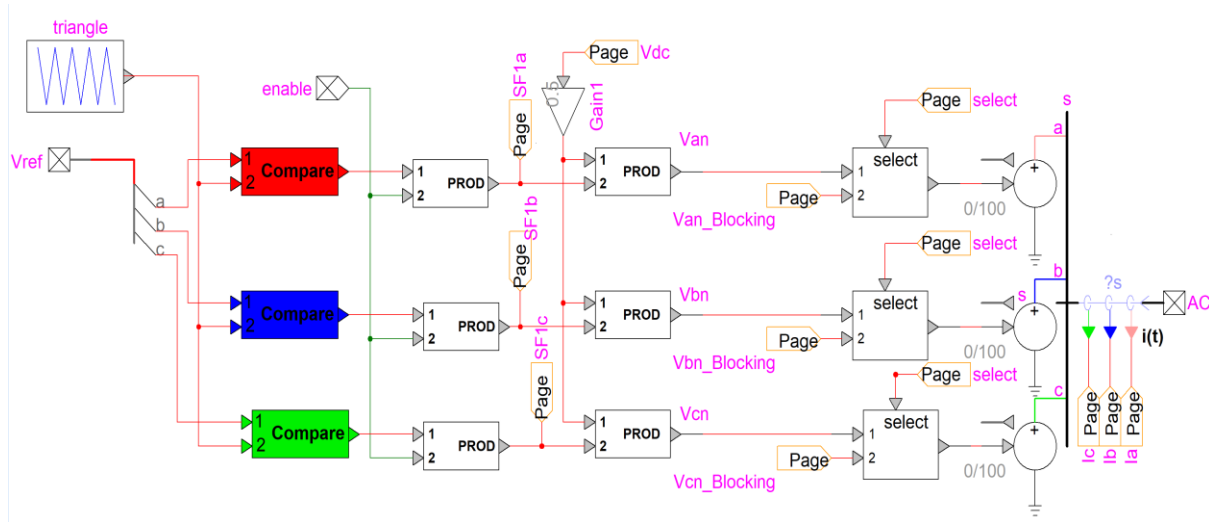


(b)

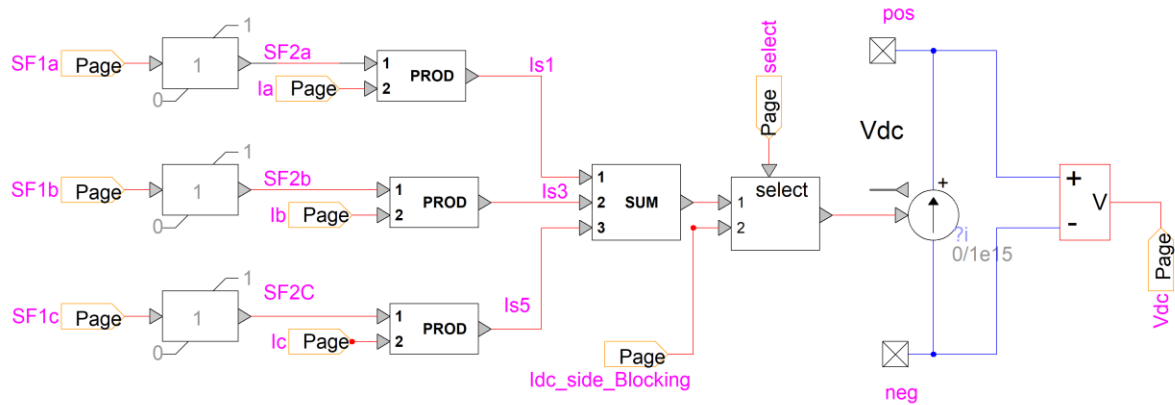
Figure 3-5 Switching function for phase a a) SF_1 b) SF_2

3.3 Implementation of Switching Function in normal operation

This section describes the implementation of the SFM in EMTP. Like in the AVM, the DC side is modeled by a controlled current source, and the AC side is modeled by a controlled voltage source. Figure 3-6 shows the implementation of the VSC as a SFM in normal operation. In this case, the DC side current source and the AC side voltage source are determined by the switching function.



(a)



(b)

Figure 3-6 SFM of the VSC in normal operation a) AC side b) DC side

In Figure 3-6a, the reference voltage of the three phases is compared with the carrier signal, and SF1 is calculated for each phase. The calculated phase voltage is modeled by the controlled voltage source.

For the DC side, SF₂ is calculated from the SF₁ for three phases. Then, the switch currents (I_{S1} , I_{S3} , I_{S5}) are calculated by the product of the inverter output currents with the corresponding switching function $SF_{a,b,c}$ as:

$$\begin{aligned}
I_{S1} &= I_a SF_{2a} \\
I_{S3} &= I_b SF_{2b} \\
I_{S5} &= I_c SF_{2c}
\end{aligned} \tag{3-5}$$

where SF_{2a} , SF_{2b} , SF_{2c} are switching functions for phases a , b , and c , respectively. The DC side current can be calculated from the switch currents by:

$$I_{DC-side} = I_{S1} + I_{S3} + I_{S5} \tag{3-6}$$

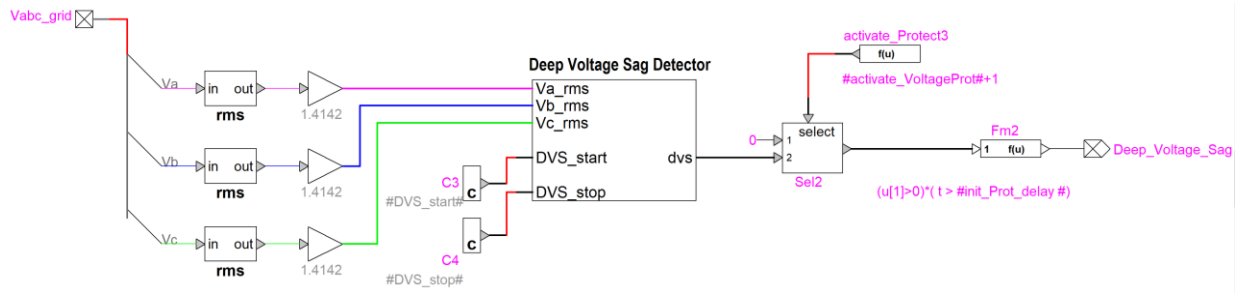
Figure 3-6b shows how the converter DC side current is calculated in EMTP.

3.4 Implementation of switching function in blocking mode

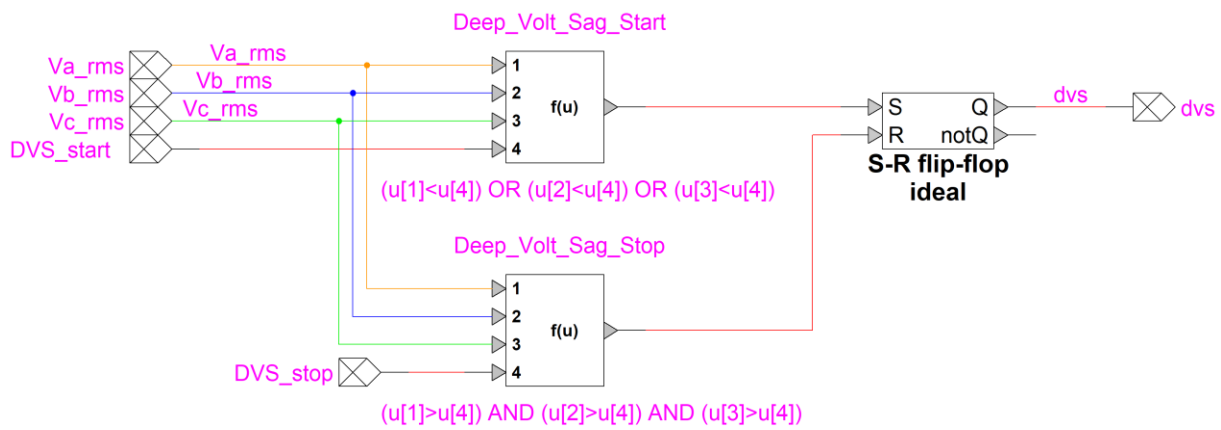
3.4.1 Blocking mode conditions

Working in either normal operation mode or blocking mode of converter depends on grid side voltage level. In this research, analysis of the VSC models is performed also in blocking mode to study their behavior at fault conditions.

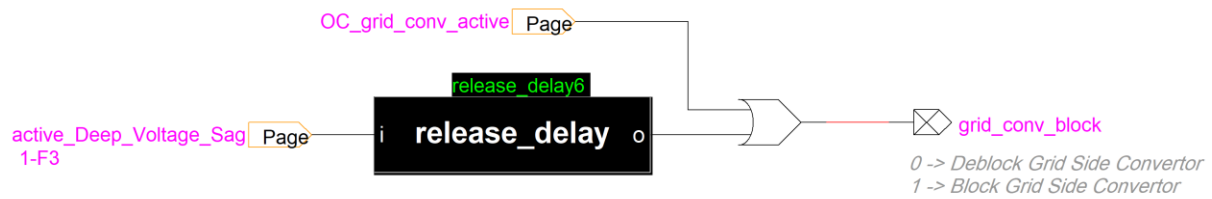
If any voltage sag is detected by the protection system, then the converter switches to blocking mode by a control signal. Figure 3-7a show the protection system for a voltage sag. Figure 3-7b illustrates the deep voltage sag detection block. In this block, the measured grid voltage is compared with the constant value of the starting/stopping dynamic scaling voltage (DVS) to detect the voltage sag. Then in Figure 3-7c, with a specified delay, the protection system activates the converter's blocking mode [7]. It should be mentioned that when no voltage sag is detected, the value of the grid converter block control signal will be equal to zero and converter will work in normal operation mode.



(a)



(b)



(c)

Figure 3-7 Protection system for voltage sag

3.4.2 Modeling of Switching Function in blocking mode

The output voltages and the DC-side current for an inverter operating in the blocking mode are also considered in EMTP, as depicted in Figure 3-8. In the blocking mode, the IGBTs are blocked, and the current flows through the antiparallel diodes. In this case, the DC side current and the AC side voltage are determined by the AC current direction. If the phase current is positive, the current is conducted by the upper leg diodes (D_1, D_3, D_5), and if the phase current is negative, the current is conducted by the lower leg diodes (D_2, D_4, D_6). Also, if the inverter output phase current is positive, the corresponding output phase voltage is $V_{DC}/2$. If the phase current is negative, the output voltage is $-V_{DC}/2$.

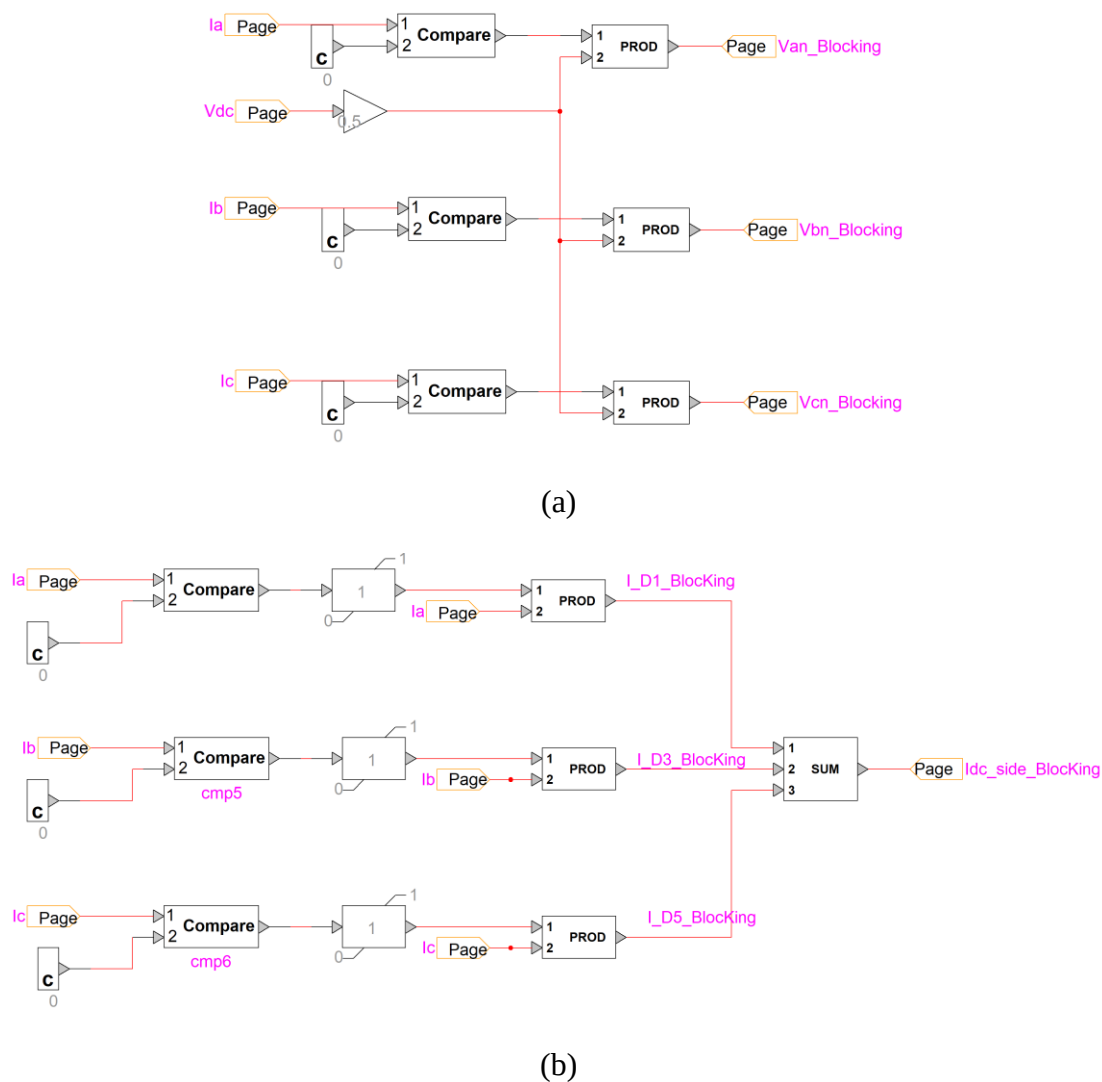


Figure 3-8 VSI model in Blocking mode a) Output voltages b) DC-side current

CHAPTER 4 PV INVERTER CONTROL

The PV system depicted in Figure 2-1 serves multiple operational objectives during both normal and faulty conditions. Under normal operating conditions, there are four control schemes employed within a nested control architecture:

- 1- The real- and reactive-power control scheme.
- 2- The DC-link voltage control scheme.
- 3- The VAr and AC-voltage control scheme.
- 4- The MPPT scheme.

These control schemes collaborate to ensure proper system functioning. The MPPT scheme determines the reference for the DC-link voltage within the DC-link voltage control loop. Subsequently, the DC-link voltage control loop establishes the reference for real power in the real- and reactive-power control scheme. Conversely, the VAr and AC-voltage control scheme determines the reference for reactive power, depending on the desired mode of operation, which can be VAr support or AC voltage regulation. Detailed discussions on these control schemes are presented in the following subsections. Before going into the details, the concepts of *abc-to-dq* transformation and the PLL-based synchronization scheme are described.

4.1 *abc-dq* Transformation

In power systems and inverter-based systems, sinusoidal time-varying signals are often converted from the *abc* reference frame to the *dq* (direct-quadrature) reference frame, where they are represented as DC signals. This transformation offers several advantages:

- i) By selecting a reference frame that rotates at the same speed as the sinusoidal quantities (synchronous speed), the time-varying sinusoidal quantities in the stationary *abc* reference frame are transformed into constant DC quantities. This simplifies the analysis and control of the system, as working with DC quantities is often more straightforward than dealing with time-varying sinusoidal quantities.
- ii) Designing controllers, such as Proportional-Integral (PI) controllers, becomes easier and more efficient when working with DC quantities. Controllers with lower-order dynamics can be designed

and implemented, which can improve the system's stability, response time, and overall control performance. This advantage is not achievable when dealing directly with sinusoidal time-varying quantities.

4.2 Synchronization Scheme

The assumption of the VSC being modeled as a controllable three-phase voltage source connected to another voltage source, such as the grid, highlights the need for a synchronization scheme in the PV system. Synchronization essentially involves determining the phase angle of the grid voltage ρ and can be achieved using various techniques. One simple approach to obtain the grid voltage angle by first decomposing the vector $\vec{v}$, as in (4-2), and representing the grid voltage into its direct and quadrature components (also referred to as the α -axis and β -axis components), as indicated in (4-1) and shown in Figure 4-1 [42].

$$\vec{v} = v_{\alpha} + jv_{\beta} \quad (4-1)$$

where the v_{α} and v_{β} are the voltage components in stationary reference frame.

$$\vec{v} = \frac{2}{3}(v_a e^{j0} + v_b e^{j\frac{2\pi}{3}} + v_c e^{j\frac{4\pi}{3}}) \quad (4-2)$$

where the v_a, v_b , and v_c are the phase voltages. Then, the sine and cosine of the angle can then be calculated as

$$\cos \rho(t) = \cos \theta(t) = \frac{v_{\alpha}}{\sqrt{v_{\alpha}^2 + v_{\beta}^2}} \quad (4-3)$$

$$\sin \rho(t) = \sin \theta(t) = \frac{v_{\beta}}{\sqrt{v_{\alpha}^2 + v_{\beta}^2}}, \quad (4-4)$$

where θ represents the angle of the grid voltage. The angle ρ is utilized for PWM and control purposes. Equations (4-3) and (4-4) depict the abc -to- $\alpha\beta$ frame transformation of v_a, v_b and v_c .

However, these three voltages are measured with respect to the (virtual) midpoint of the DC-link voltage, which may not physically exist or be easily accessible. This issue can be resolved by obtaining v_α and v_β from the abc -to- $\alpha\beta$ frame transformation of the grid phase voltages with reference to a common electrical node, such as phase c itself. To understand the process, let us compare the space vector corresponding to v_{ab}, v_{bc} and $v_{cc} = 0$, with the space vector corresponding to v_a, v_b and v_c , in (4-2). By eliminating $e^{(j4\pi/3)}$ in (4-2) based on the identity $e^{(j0)} + e^{(j2\pi/3)} + e^{(j4\pi/3)} = 0$ and reordering the terms, we obtain

$$\vec{v} = \frac{2}{3}(v_{ac}e^{j0} + v_{bc}e^{j\frac{2\pi}{3}} + 0e^{j\frac{4\pi}{3}}) \quad (4-5)$$

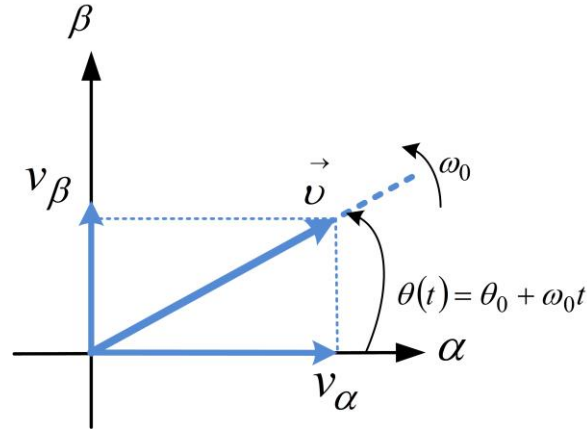


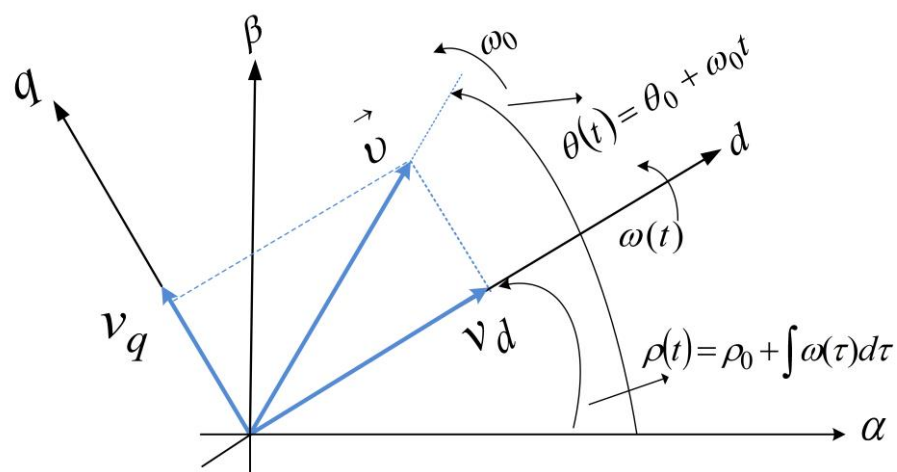
Figure 4-1 Extraction of the grid voltage angle by means of $\alpha\beta$ -frame transformation [42]

The α - and β -axis components of the vectors given by (4-2) and (4-5) are equivalent. It is worth noting that instead of using the individual phase voltages v_a, v_b , and v_c , the grid voltage vector can also be constructed using the line-to-line voltages, v_{ab}, v_{bc} , and v_{cc} mentioned in (4-3). However, this resultant vector is scaled by a factor of $\sqrt{3}$ and phase-shifted by $\pi/6$ radian compared to the vector represented by (4-2). The technique described earlier for extracting the angle works well when the three-phase voltage is balanced and has low harmonic distortion. However, if the voltage is unbalanced and/or distorted, the extracted angle will be distorted as well and not suitable for control purposes. In such cases, a phase-locked loop (PLL) is commonly used to accurately extract the angle of the positive-sequence fundamental component of the grid voltage.

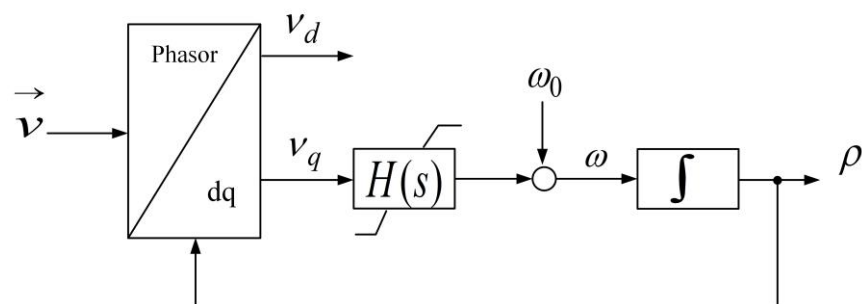
In a PLL, the vector $\vec{v}$ is projected onto the d and q axes of a dq frame, as depicted in Figure 4-2(a). The frame is then rotated to ensure that v_q becomes zero. This objective is accomplished through the closed-loop mechanism shown in Figure 4-2(b). Any deviation of v_q from zero is processed by a filter, $H(s)$, which translates it into an adjustment of the rotational speed of the dq frame relative to the nominal frequency of the power system, ω_0 . In steady state, v_q settles at zero, aligning the d axis of the dq frame with the grid voltage vector, and the rotational speed of the dq frame becomes equal to the angular frequency of the grid [103]. Consequently, the extracted angle ρ becomes equivalent to the grid voltage angle θ .

For stability and robustness, $H(s)$ must have at least one pole at $s = 0$, while the other poles and zeros are determined based on specific criteria. Furthermore, the frequency response of $H(s)$ can be designed to mitigate the impact of grid voltage imbalance and distortion on ρ . It is important to note that the PLL also provides an estimate of the grid's instantaneous frequency ω , which is the derivative of the grid voltage angle θ with respect to time, i.e., $(d\theta/dt)$.

To restrict deviations of the network frequency from ω_0 , particularly in situations like islanding events, and to prevent integrator wind-up, it is necessary to incorporate a saturation block that limits the output of $H(s)$, as depicted in Figure 4-2.



(a)



(b) [42]

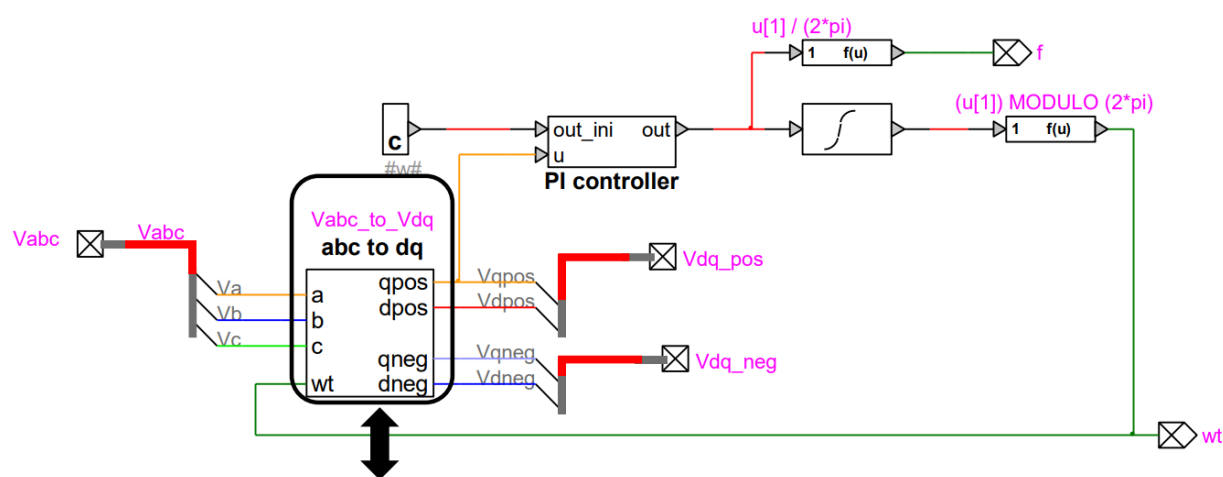


Figure 4-2 (a) Vector diagram illustrating the operation principle of a phase-locked loop (PLL).

(b) Block diagram of the PLL (c) PLL block diagram in EMTP

In scenarios where the utility conditions are ideal, without any imbalances or harmonics, the Synchronous Reference Frame PLL performs well. However, when high-order harmonic voltages are present, the PLL bandwidth can be reduced to minimize the impact of these harmonics on the output.

However, in the case of voltage unbalancing, simply reducing the bandwidth is not a suitable solution. This is because the dynamic behavior of the PLL system becomes severely affected, resulting in a significant deterioration of the PLL output quality. Figure 4-2c illustrates such situations, where the unbalanced voltage vector, comprising positive and negative sequence components, is represented in a double synchronous reference frame [104].

4.3 GSC control

The control of the GSC is accomplished by employing vector control schemes. Decoupled control of real and reactive powers is possible by using vector control. Exploiting Park's transformation, the phase variables are transformed to the q - and d -axis in a rotating reference frame. The control scheme used by EMTP is depicted in Figure 4-3. In this figure, i_{dgsc} and i_{qgsc} are the q - and d -axis currents of the GSC, V_{DC} is the DC bus voltage, and V_{MV}^+ is the positive sequence voltage at the PV park transformer MV terminal. In the control scheme presented in this figure, i_{dgsc} is used to keep V_{DC} and i_{qgsc} is used to control V_{MV}^+ [105].

A two-level controller is used to control the GSC. The inner controller provides the switching firing and controls the converter's output voltage; the outer controller generates the reference d - q frame currents (i'_{dgsc} and i'_{qgsc}). The inner controller is faster than the outer controller.

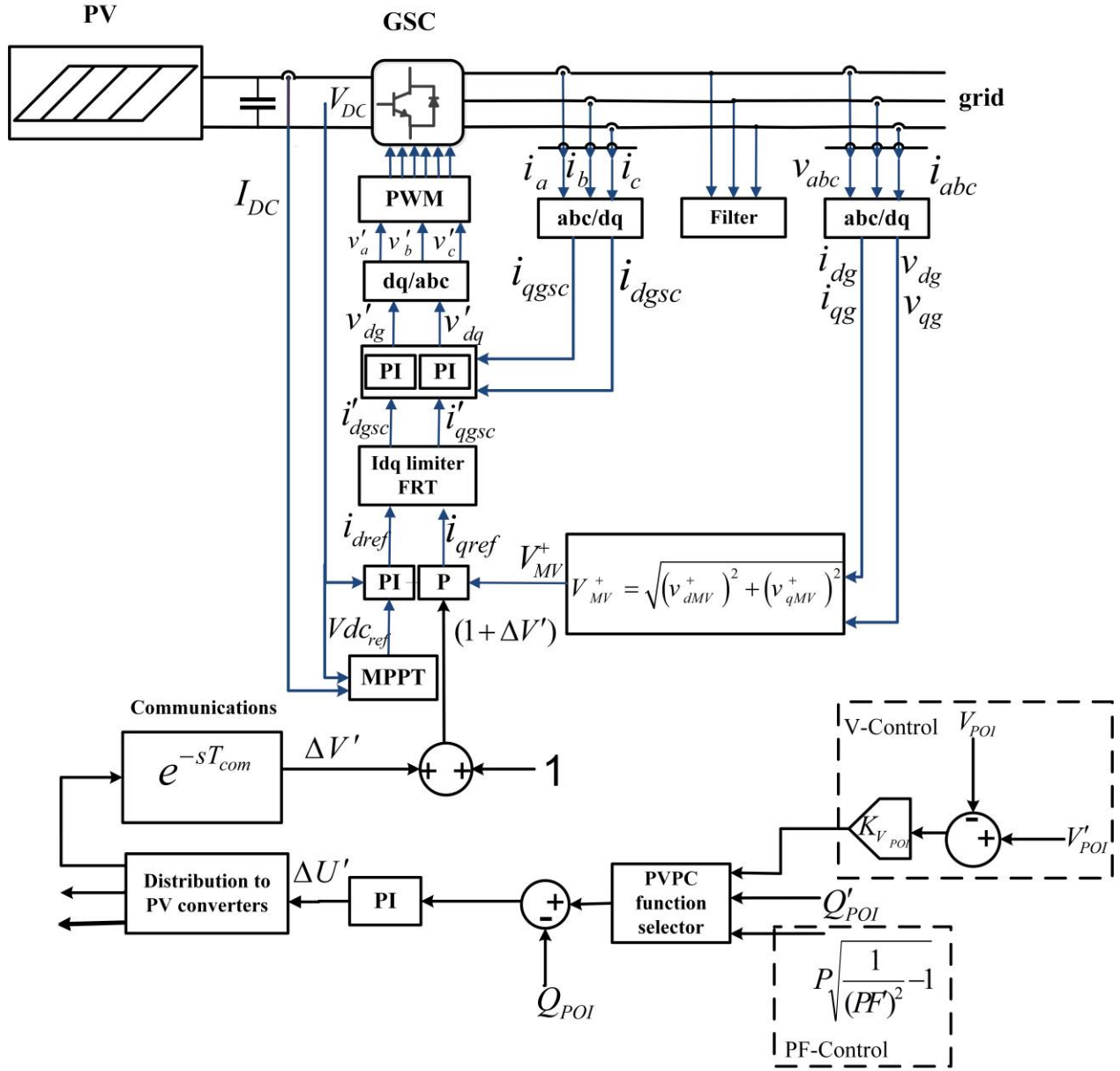


Figure 4-3 Schematic diagram of PVPC and GSC control [105]

It is well-known that weather conditions affect PVP active power. However, based on the grid code, a PVP should also participate in reactive power control at the point of interconnection (POI). As shown in Figure 4-3, there are two primary and secondary voltage controls for the PVP. At the main level, the positive sequence of inverter terminal voltage (V_{mv}^+) is controlled using the proportional voltage regulator. In the next level, the PVPC adjusts the PV inverters reference voltage (V') through a proportional-integral (PI) reactive controller [106]. This is done by

monitoring the reactive power at POI (Q_{POI}). The PVPC may also contain voltage control (V-control) and power factor control (PF-control) functions.

As shown in Figure 4-3, the q -axis reference current is calculated by the proportional outer voltage control, as indicated by (4-6)

$$i_{qref} = K_v (V' - V_{mv}^+) \quad (4-6)$$

Where K_v is the voltage regulator gain. The reference for the positive sequence voltage for the PV inverters at the MV terminal of the transformer (V') is calculated by the PVPC. The positive sequence voltage at the MV side of PV array transformer is not directly measured by the PV inverter controller; this is approximated by [7]:

$$V_{MV}^+ = \sqrt{(V_{dMV}^+)^2 + (V_{qMV}^+)^2}, \quad (4-7)$$

where

$$\begin{aligned} V_{dMV}^+ &= V_{dLV}^+ + R_{tr} \times I_{dPVI}^+ - X_{tr} \times I_{qtr}^+ \\ V_{qMV}^+ &= V_{qLV}^+ + R_{tr} \times I_{qPVI}^+ + X_{tr} \times I_{dtr}^+ \end{aligned} \quad (4-8)$$

In (4-8), V_{dMV}^+ and V_{qMV}^+ are the d -axis and q -axis positive sequence voltage at the MV side of the PV array transformer, V_{dLV}^+ and V_{qLV}^+ are the d -axis and q -axis positive sequence voltage at LV side of PV array transformer, I_{dtr}^+ and I_{qtr}^+ are the d -axis and q -axis positive sequence currents at LV side of PV array transformer, R_{tr} and X_{tr} are the resistance and reactance values of the PV array transformer [7].

4.3.1 PV inverter GSC Decoupled Sequence Control

The GSC control system plays an important role in PVP simulation. The excellent operation of the grid connected PVP, depends on the fast and accurate control schemes. The different controllers have been used in the literature for the PV systems, such as the nonlinear controllers [107-109], robust controllers [107-111], adaptive controllers [112-114], predictive controllers [115, 116], optimal controller [117, 118], and the intelligent controllers [119, 120].

A control scheme with two control loops, one for the positive sequence and another one for the negative-sequence currents is proposed in [121]. This is outlined in the following.

During either a fault or unbalanced loading condition, the coupled sequence control of GSC does not inject any negative sequence currents into the grid. However, in real systems a very small amount of negative sequence currents is injected into the grid because of the phase shift in low pass measuring filters. On the other hand, the terminal voltages of GSC consist of negative sequence components during the above-mentioned conditions. This negative sequence component makes GSC output active power and DC voltage have second harmonic oscillations [105]. These second harmonic oscillations can be eliminated using a decoupled sequence control (DSC) scheme [122]. This control scheme is already implemented in EMTP. In this control scheme, the positive sequence reactive currents have the priority to use the converter capacity. Then, the rest of the converter capacity can be used for the second harmonic oscillation mitigation [123]. The instantaneous active power of an unbalanced grid is as [121]:

$$p = P_0 + P_{C2} \cos(2\omega t) + P_{S2} \sin(2\omega t) \quad (4-9)$$

where P_0 is the average value of the active power, P_{C2} and P_{S2} are the magnitudes of the second harmonic fluctuating terms. These parameters can be calculated as [122]:

$$\begin{aligned} P_0 &= v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^- \\ P_{C2} &= v_d^- i_d^+ + v_q^- i_q^+ + v_d^+ i_d^- + v_q^+ i_q^- \\ P_{S2} &= v_q^- i_d^+ - v_d^- i_q^+ - v_q^+ i_d^- - v_d^+ i_q^- \end{aligned} \quad (4-10)$$

where $v_{d,q}^+$, $i_{d,q}^+$, $v_{d,q}^-$, and $i_{d,q}^-$ are the positive and negative sequence components of voltage and current in rotating reference frame, respectively. The GSC current references (I_{dgs}^+ , I_{qgs}^+ , I_{dgs}^- , I_{qgs}^-) are calculated to cancel out the active power oscillations terms. These references are calculated as [122]:

$$\begin{bmatrix} i_{qgsc}^{'+} \\ i_{dgsc}^{'+} \\ i_{qgsc}^{'-} \\ i_{dgsc}^{'-} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ v_{qg}^{+} & v_{dg}^{+} & v_{qg}^{-} & v_{dg}^{-} \\ v_{qg}^{-} & v_{dg}^{-} & v_{qg}^{+} & v_{dg}^{+} \\ -v_{dg}^{-} & v_{qg}^{-} & v_{dg}^{+} & -v_{qg}^{+} \end{bmatrix}^{-1} \begin{bmatrix} i_{qgsc}^{'} \\ P_0 \\ P_{C2} \\ P_{S2} \end{bmatrix} \quad (4-11)$$

Failure of the negative sequence fault current injection by PV may cause the protection system to malfunction under certain unbalanced faults. However, this issue is solved by DSC [124]. The performance of GSC decoupled sequence control is limited to GSC rating as well as the FRT requirement specified by the grid code. If GSC current output surpasses its maximum value, the total elimination of second harmonic oscillations cannot be accomplished. It is worth mentioning that a larger amount of GSC currents is needed to remove the second harmonic oscillations and attain FRT requirements as well [105].

In [105], a DSC has been proposed to decrease the chance of protection system misoperation. In [2], LVRT processes have been analyzed, and a unified controller has been proposed by updating the positive and negative current references. For enhancement of the FRT ability of large PVP, positive and negative sequence control schemes has been proposed in [125].

4.4 Maximum Power Point Tracking (MPPT) Scheme

The PV module produces the maximum amount of DC power with a specific DC voltage based on the received solar radiation and its temperature. This is known as Maximum Power Point (MPP).

In a PV system, in order to extract its maximum power, a DC voltage controller is used to regulate the PV module voltage at this MPP voltage. There are several MPPT techniques proposed in literature, such as Perturb and Observe (P&O) technique, Incremental Conductance method, Artificial Neural Network method, Fuzzy Logic method, etc. Among them, the P&O and IC method, and their variants are the most utilized [41].

In EMTP, when MPPT control is enabled, it is assumed that the PV park operates at its maximum capacity as determined by the atmospheric conditions specified by the user. However, it should be mentioned that the most recent EMTP version does not include a model for the MPPT controller.

As a result, if there are variations in irradiance during the simulation, the power reference remains constant and does not adapt accordingly.

CHAPTER 5 SIMULATION AND MODEL COMPARISON RESULTS

In this chapter, the PVP VSC-based models, DM, AVM, and SFM, are compared in terms of accuracy and computational speed under steady-state and transient conditions. The DM is taken as basis for the comparison. The system illustrated in Figure 5-1 is used as test network. The dynamics of the voltage and current of PV park at the PCC are presented before, during, and after three-phase to ground fault. The transient scenario consists of a three-phase fault occurring in BUS3 at $t = 0.2s$ and clears at $t = 0.4 s$, and for all simulations the time step is assumed of $20 \mu s$.

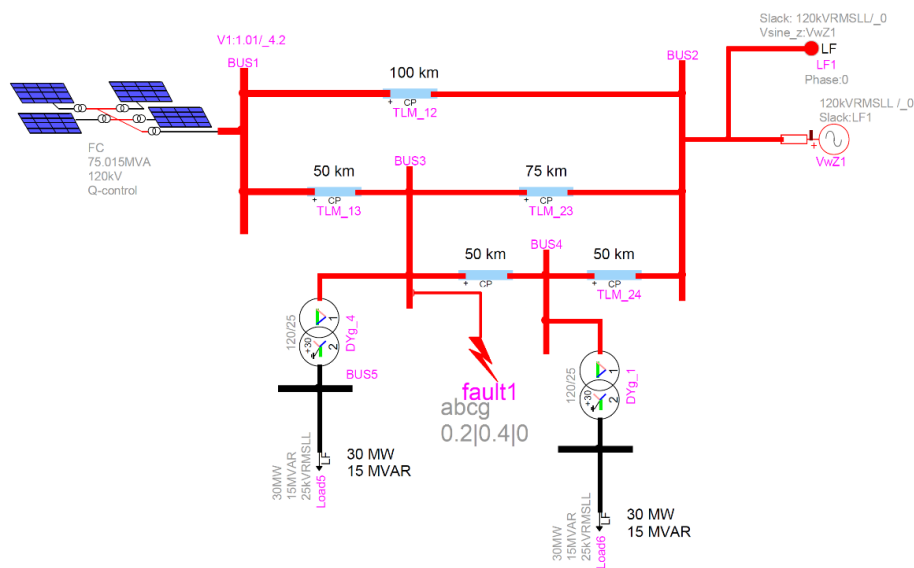


Figure 5-1 Test Network [126]

5.1 Comparison of the three different converter models (DM, AVM, SFM)

Figure 5-2 shows the PCC voltage of phase a , when the inverter works in the fault ride through region (FRT). It can be seen in Figure 5-2 that SFM, AVM, and DM are in good agreement. A more detailed analysis follows.

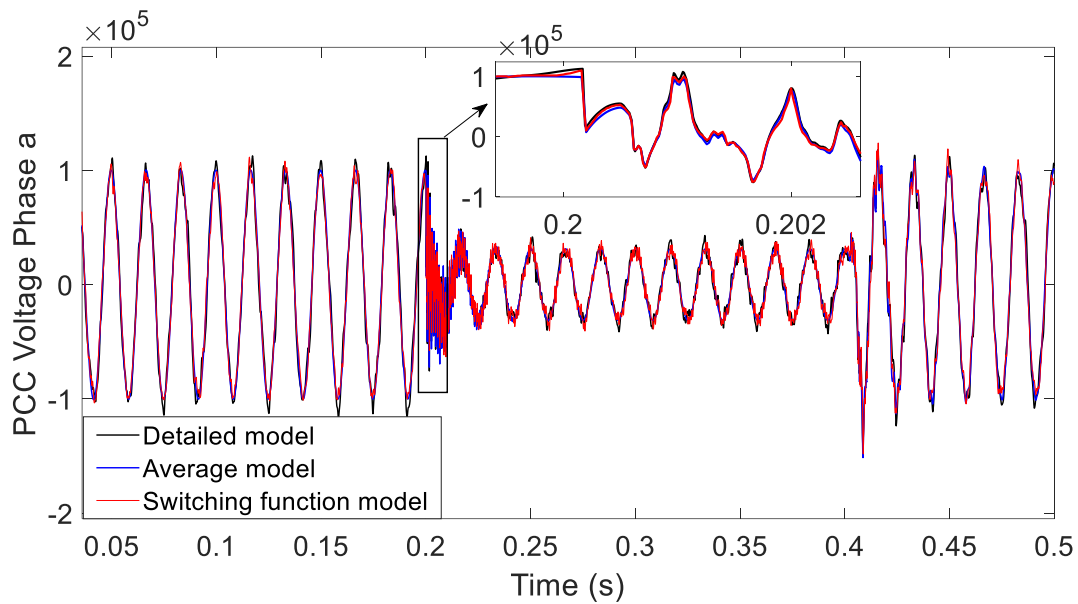


Figure 5-2 PCC voltage phase a (normal operation)

Figure 5-3 presents the absolute error between AVM/SFM and DM. In the top figure (AVM), the maximum error occurs around $t = 0.4$ s (clearing time). As for the SFM, the maximum error is located around $t = 0.2$ s, and this error is equal to 60kV. From Figure 5-3 it is observed that, in the overall, AVM incurs in larger absolute error than SFM. As more a representative indicator, the *rms* errors by AVM and SFM are of 11.32% and 8.38%, respectively, showing a closer agreement between SFM and DM waveforms.

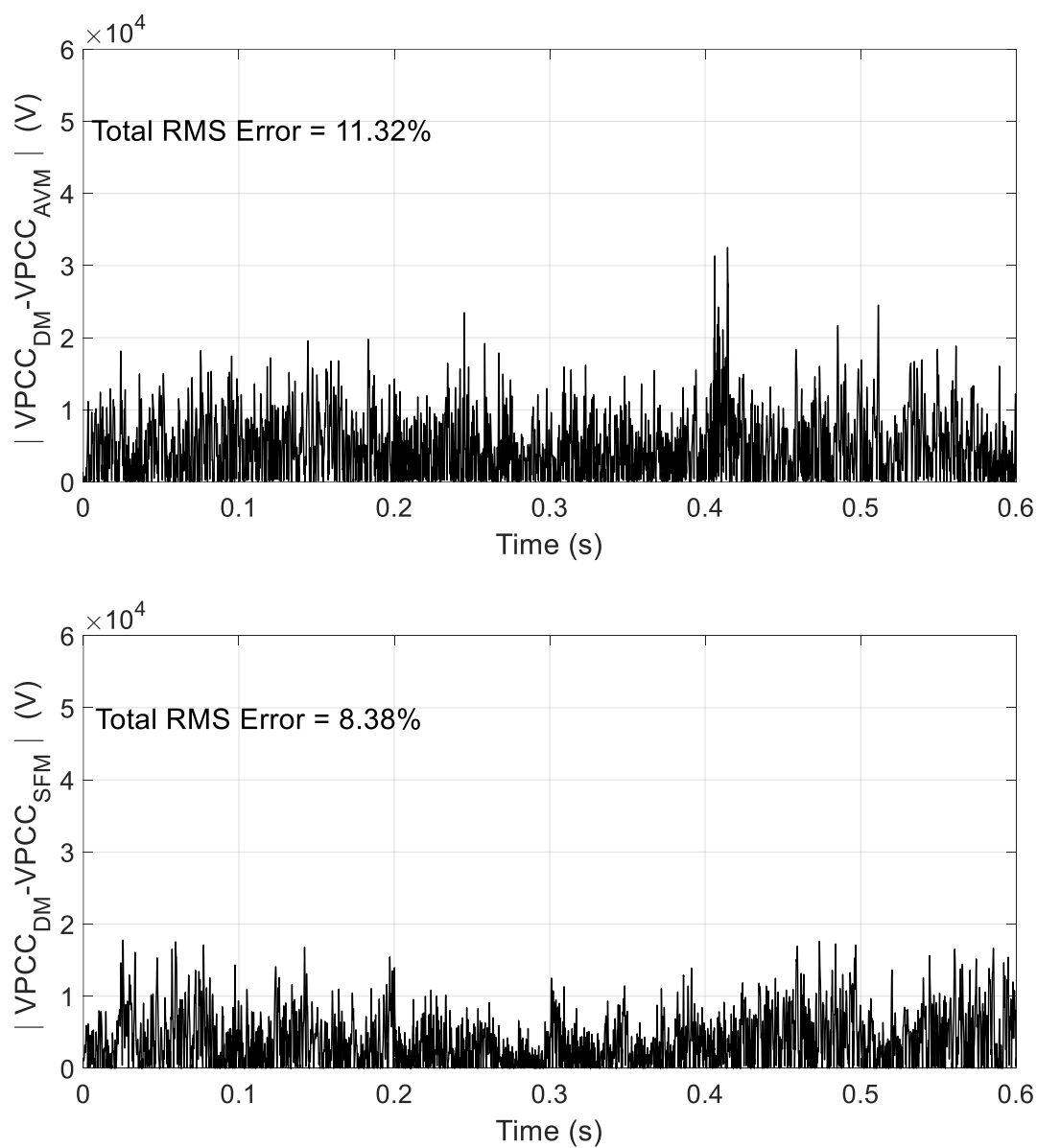


Figure 5-3 Absolute value of the difference of PCC voltage results from the DM, AVM and SFM in normal operation

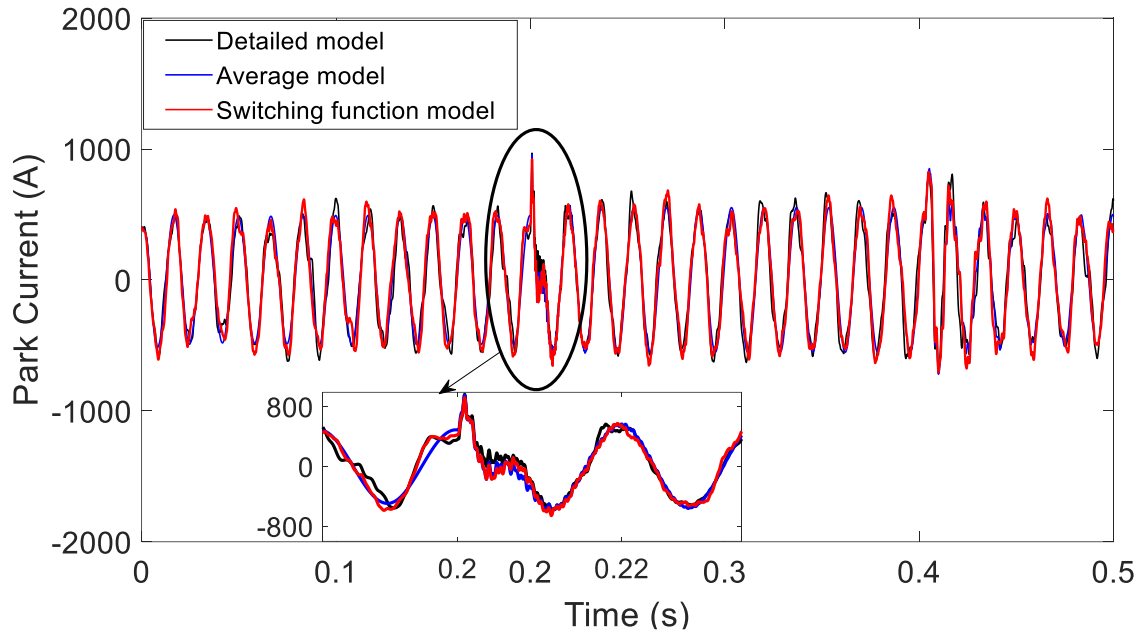


Figure 5-4 Park current phase a (normal operation)

Figure 5-4 presents the current for phase a delivered by the PVP considering normal operation mode of the converter. It can be seen that in this operation mode, SFM and AVM agree to DM. However, before and after the fault ($t = 0.2$ s) the SFM is more accurate than AVM. The corresponding absolute errors are presented in Figure 5-5. The *rms* errors by AVM and SFM are of 24.57% and 17.65%, respectively.

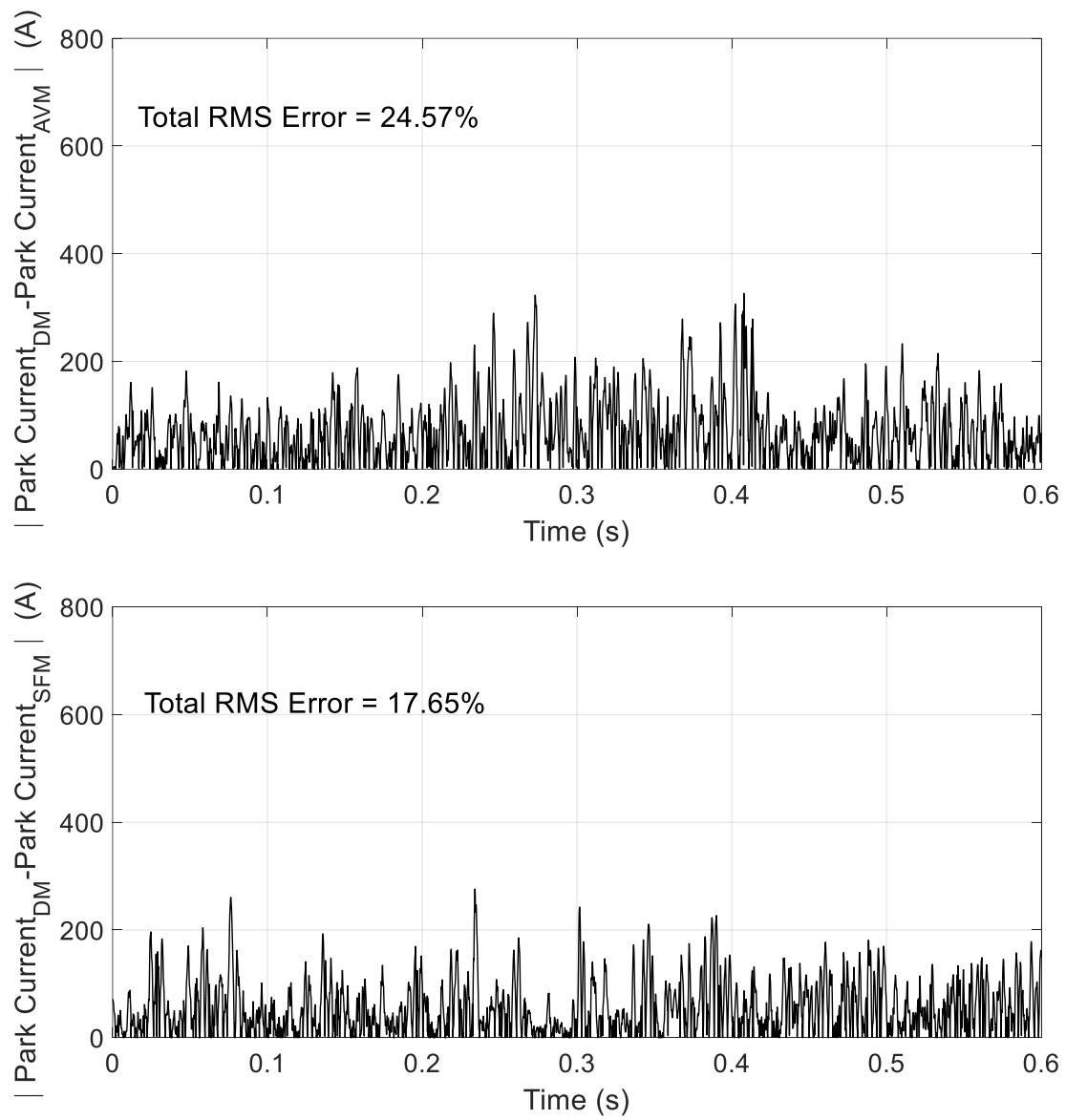


Figure 5-5 Absolute value of the difference of park current results from the DM, AVM, and SFM in normal operation

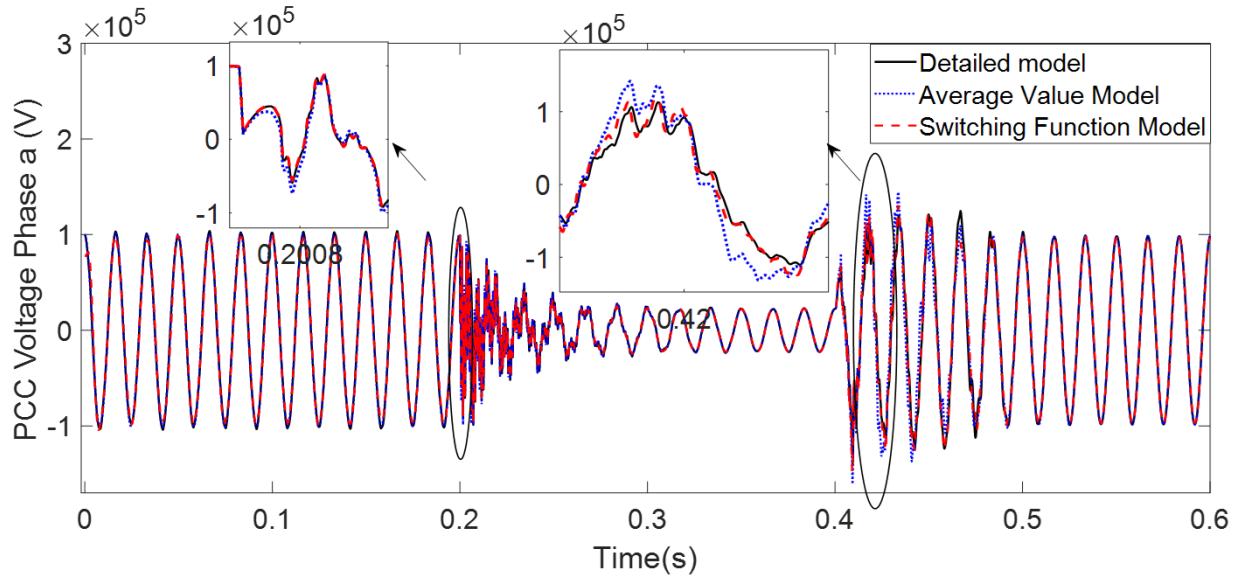


Figure 5-6 PCC voltage phase a (Blocking mode)

Figure 5-6 depicts the voltage for phase a at the PCC when the inverter works in blocking mode. According to the waveforms in Figure 5-6 PCC voltage phase a (Blocking mode), The absolute errors are included in Figure 5-7. This figure shows that in the overall, the error for the SFM is smaller than AVM. The *rms* errors by AVM and SFM are of 16.08% and 4.63%, respectively.

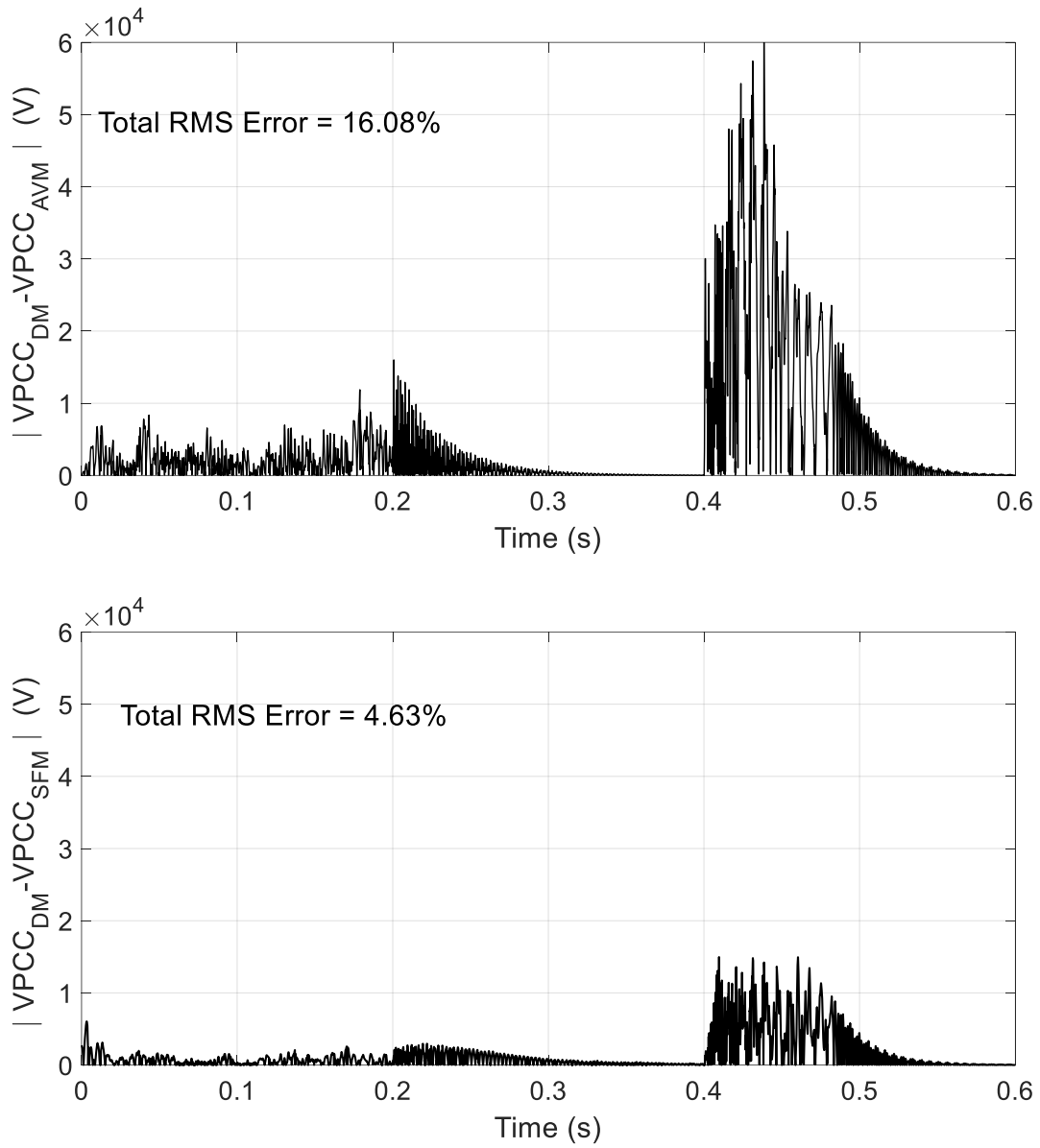


Figure 5-7 Absolute value of the difference of PCC voltage results from the DM, AVM, and SFM in blocking mode SFM

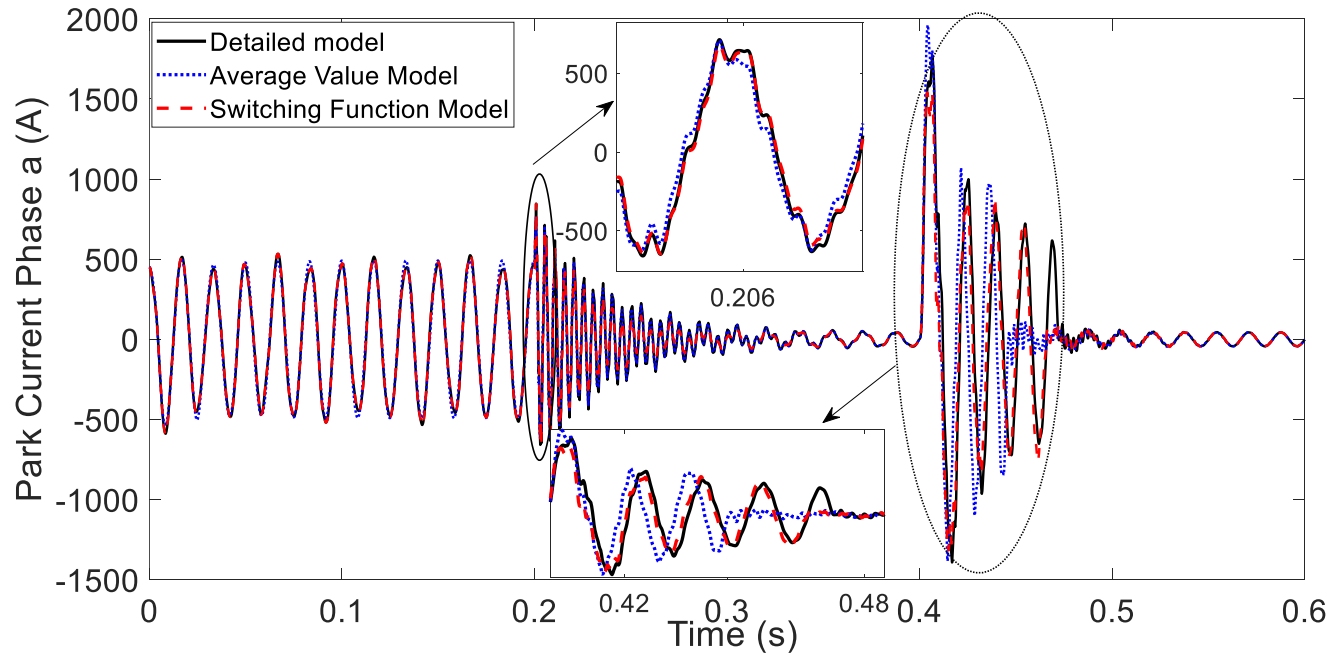


Figure 5-8 Park current phase a (Blocking mode)

Figure 5-8 shows the current, phase a , delivered by the PVP operating in blocking mode. From Figure 5-8, one can observe that the SFM results are closer to the DM than AVM, and there is considerable difference between the AVM and DM after clearing the fault. This can be justified by the fact that the blocking mode of the AVM consists of 3 ideal switches. However, in a real converter the currents still flow through antiparallel diodes. These conditions can be modeled by the SFM and DM.

The absolute errors between SFM/AVM and DM are presented in Figure 5-9. The *rms* errors by AVM and SFM are of 69.73% and 16.07%, respectively.

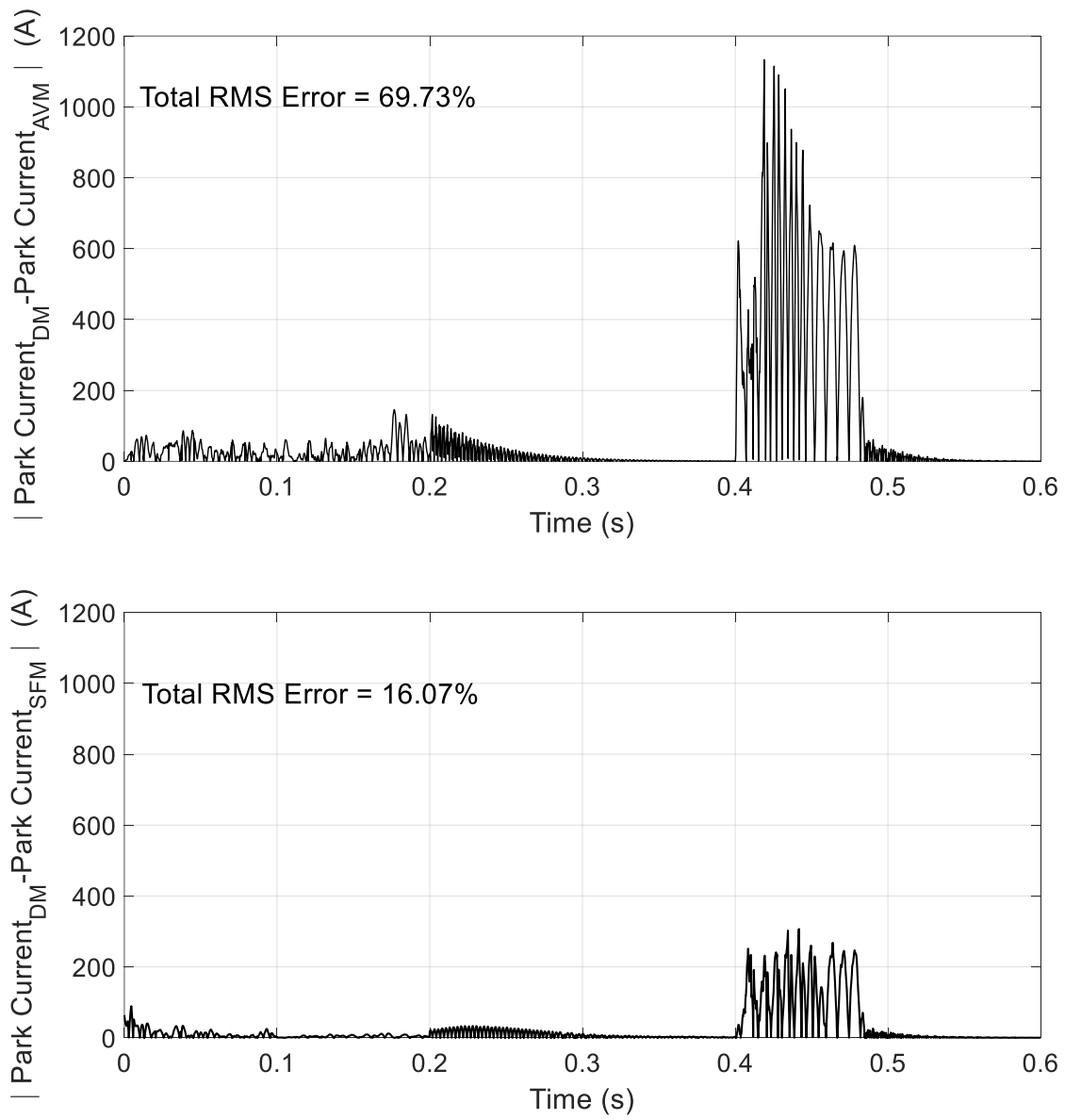
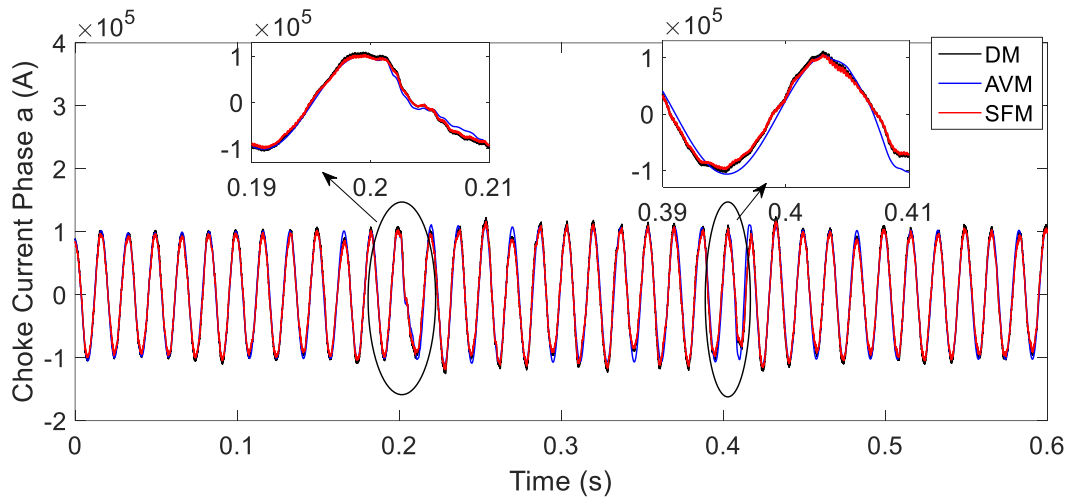


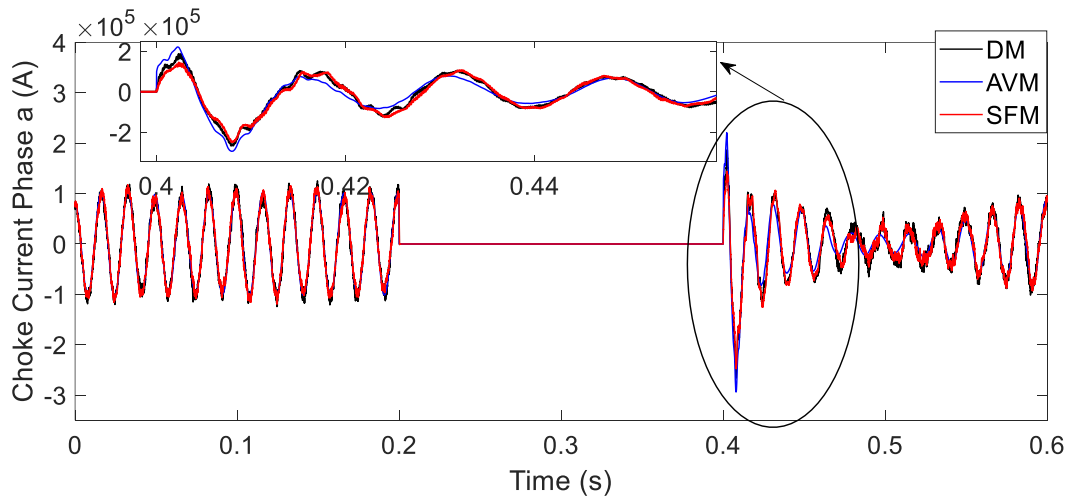
Figure 5-9 Absolute value of the difference of park current results from the DM, AVM, and SFM in blocking mode

5.2 Comparison of the VSC output current before filtering (Choke Current)

To further compare the performance of each converter model, the choke current is calculated in both normal operation and blocking mode condition. Like in Section 3.3.1 a three-phase fault occurs in BUS3 in $t = 0.2$ s and clears in $t = 0.4$ s. Figure 5-10 shows the choke current waveform as given by DM, AVM, and SFM. It can be observed in Figure 5-10 that, in both modes, AVM does not provide good accuracy after clearing the fault.



(a)



(b)

Figure 5-10 Choke current phase a in a) normal operation b) blocking mode

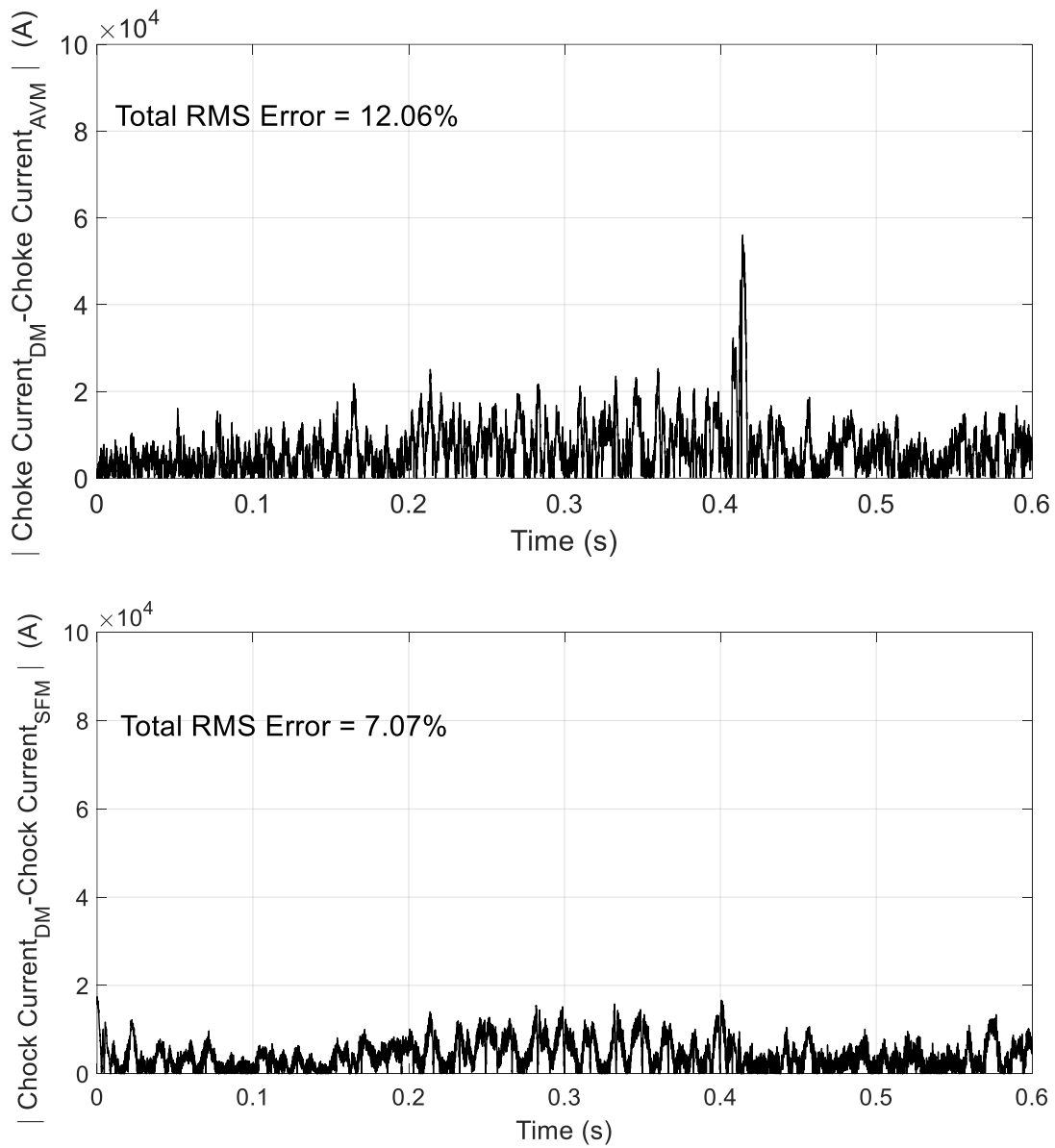


Figure 5-11 Absolute value of the difference of RL-Choke current obtained from the DM, AVM, and SFM in normal operation

Figure 5-11 depicts the absolute values between AVM/SFM and DM for normal operation. The *rms* errors by AVM and SFM are of 12.06% and 7.07%, respectively.

Figure 5-12 illustrates the absolute values between AVM/SFM and DM for blocking mode. The *rms* errors by AVM and SFM are of 22.34% and 7.93%, respectively.

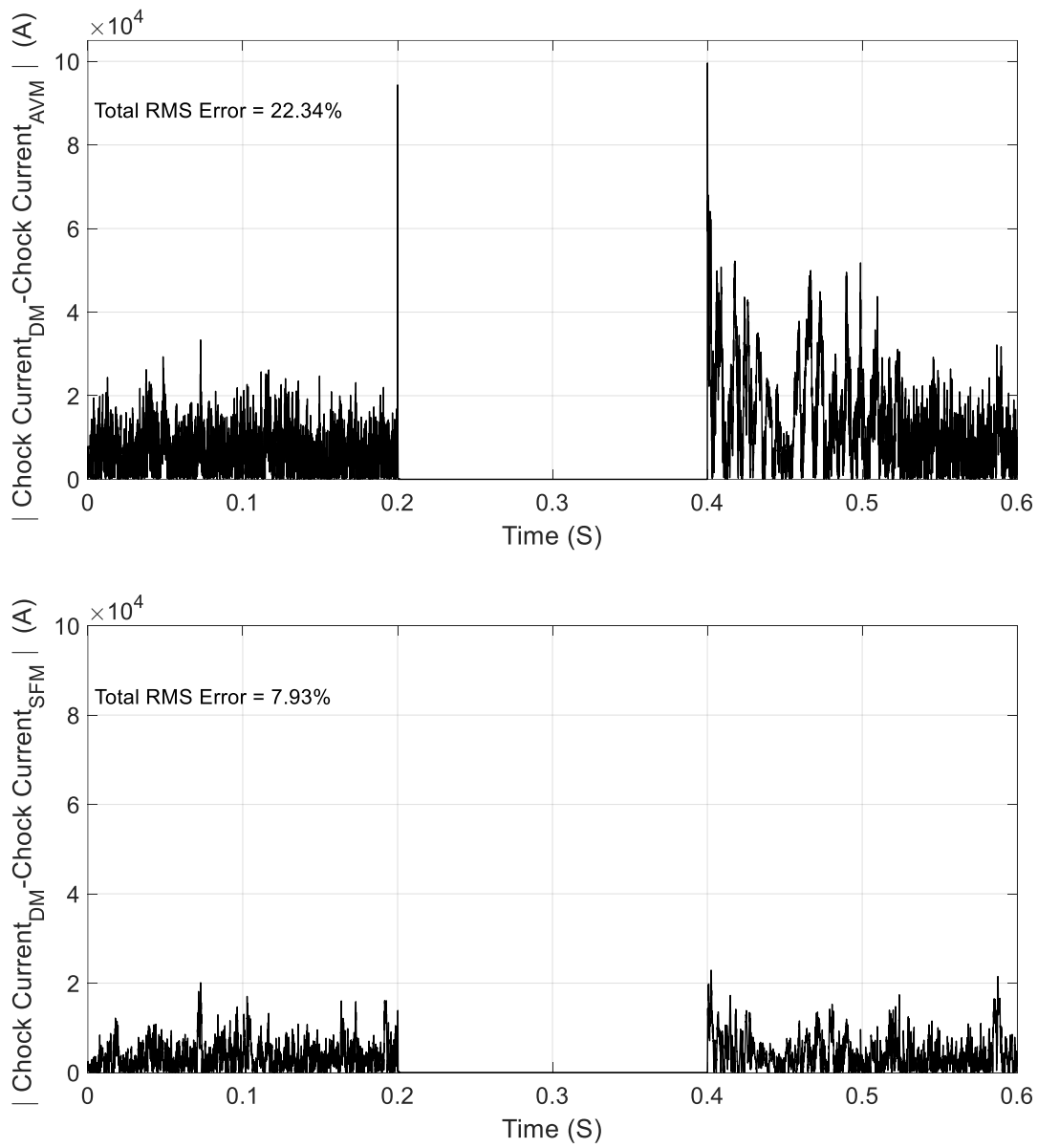


Figure 5-12 Absolute value of the difference of choke current results from the DM, AVM, and SFM in blocking mode

5.3 Comparison of the simulation time

To compare the computational efficiency of the DM, AVM, and SFM, the aggregated model used in Figure 5-1 is replaced with a detailed PVP model (see Figure 5-13). This includes three feeders with PV modules. A 2 s time-window simulation of the system is conducted using a time step of $10\ \mu\text{s}$ in EMTF. A three-phase fault occurs in BUS3 at $t = 0.5\text{ s}$ and clears at $t = 0.7\text{ s}$. Figure 5-14 and Figure 5-15 show the voltage and current, phase a , at the PCC when the inverter works in normal operation mode. The summary of the CPU time for each model is listed in Table 5.1 and Table 5.2 in normal operation and blocking mode and are compared with the aggregated model results. Comparison of the execution time for the DM, AVM, and SFM reveals that the AVM is faster than SFM for both detailed and aggregated PV park, as expected.

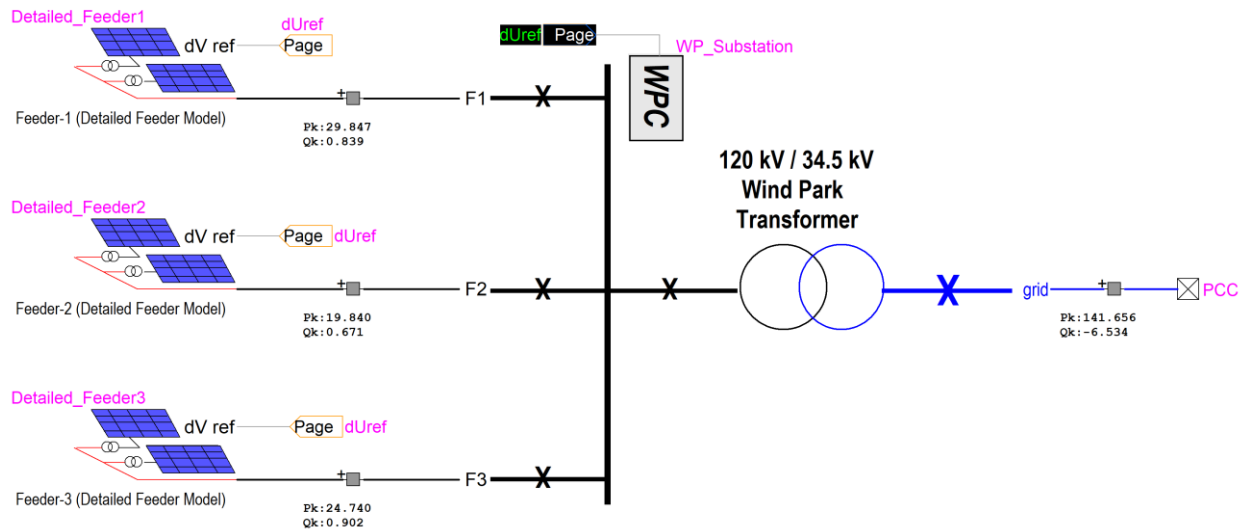


Figure 5-13 Detailed PVP with three feeders

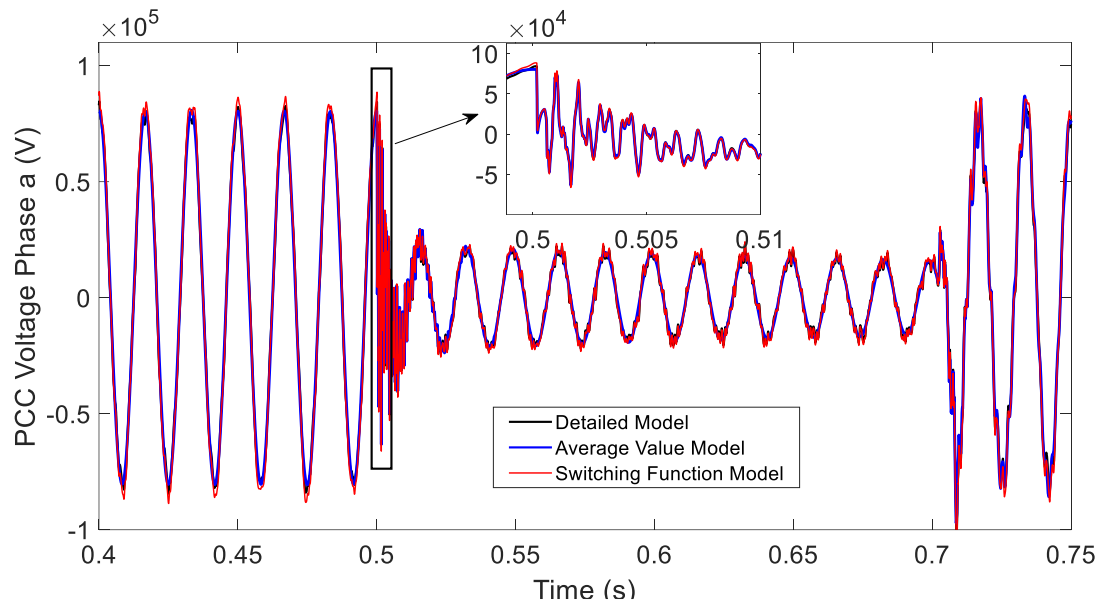


Figure 5-14 PCC voltage phase a (normal operation)

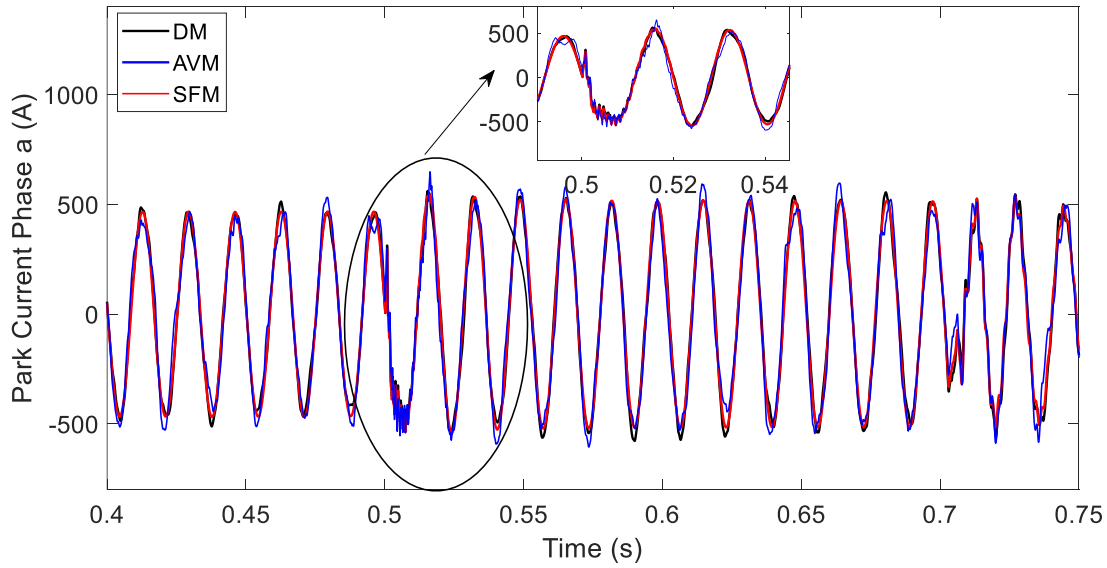


Figure 5-15 Park current phase a (normal operation)

Table 5.1 Summary of CPU-time (in seconds) for each model in normal operation

Model	Detailed Park Model			Aggregated Park Model		
	DM	AVM	SFM	DM	AVM	SFM
Prepare data	0.85	0.89	0.84	0.04	0.04	0.03
Read data	0.03	0.02	0.01	0	0	0
Device initialization	1.66	1.47	1.28	0.007	0.007	0.007
Steady-state solution	0.178	0.11	0.11	0.015	0.007	0.015
Time-domain $Ax = B$ solution	513	117	173	15.89	0.61	0.89
Solution of control systems	507	498	598	12	10	14
Time-domain solution	1070	662	805	30	13	17
Total	1098	689	829	30	13	17

Table 5.2 Summary of CPU-time (in seconds) for each model in blocking mode

	Detailed Park Model			Aggregated Park Model		
Model	DM	AVM	SFM	DM	AVM	SFM
Prepare data	0.87	1.06	0.86	0.47	0.03	0.047
Read data	0.015	0.031	0.015	0	0	0
Device initialization	1.64	1.70	1.33	0.015	0.015	0.015
Steady-state solution	0.15	0.42	0.12	0.047	0	0
Time-domain $Ax = B$ solution	500	97	146	9.81	0.84	0.98
Solution of control systems	599	558	674	12.84	11.04	14.58
Time-domain solution	1151	701	861	24.79	13.86	17.72
Total	1180	731	890	24.92	13.97	17.92

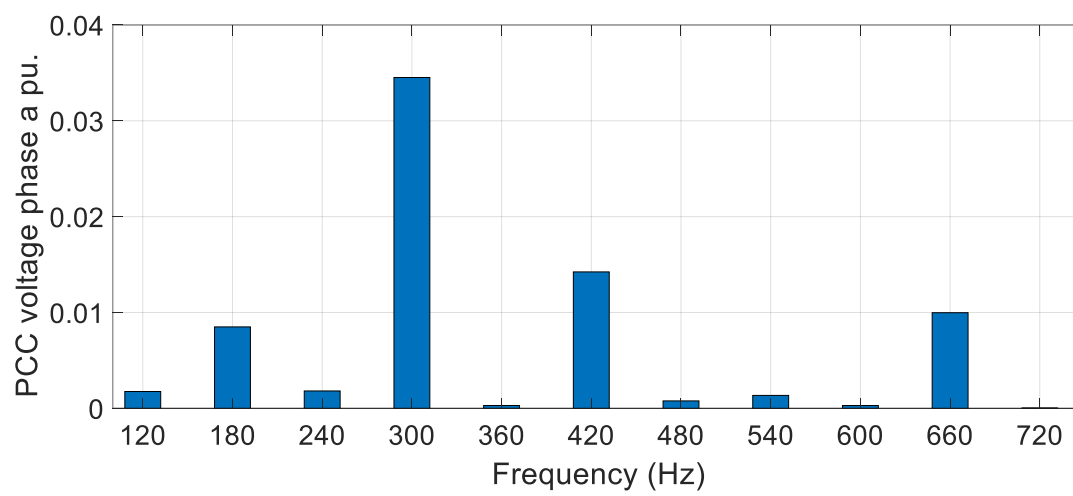
While the CPU times remain largely consistent between the normal and blocking modes due to the brief duration of the fault, it is crucial to emphasize that the waveforms do not align.

5.4 Harmonic analysis of the models

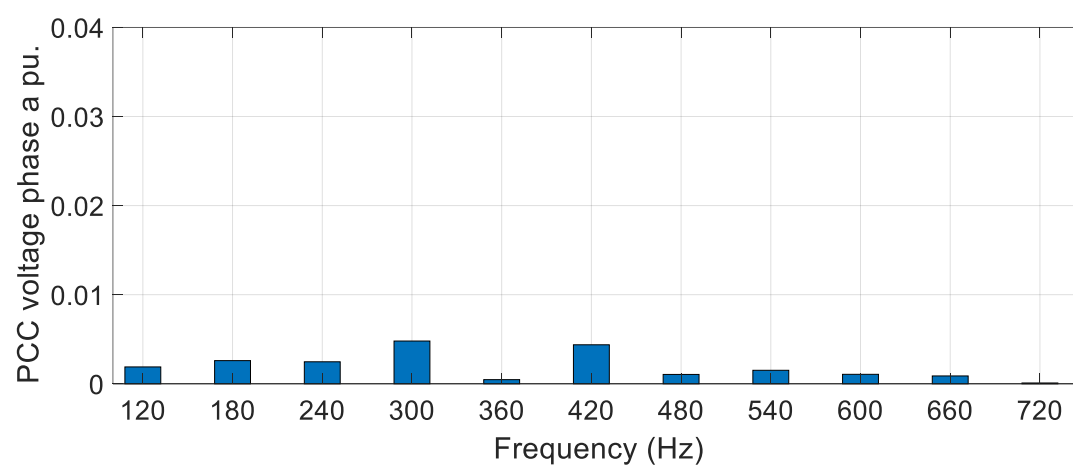
To compare the harmonic content in the waveforms by both DM and SFM, the aggregated PVP shown in Figure 5-1 is simulated in steady-state conditions. The switching frequency of converter is 4.5 kHz. It should be mentioned that AVM does not allow to observe high-frequency ripple and it is not included in the following comparisons.

Figure 5-16 shows the harmonic content of the voltage at the PCC, as given by DM and SFM. These results are obtained with the fast Fourier transform (FFT) algorithm. The fundamental component has a normalized amplitude of 1 pu, and it is not shown in Figure 5-16 for better visibility of other harmonic components. Based on the results achieved, both DM and SFM models offer valuable insights into the harmonic features of voltage and current waveforms.

Figure 5-17 presents the harmonic content, as given by DM and SFM, of the current, phase a , delivered by the PVP. Furthermore, the total harmonic distortion (THD) of the DM and SFM are summarized in Table 5.3. In this table, the results of the detailed PVP are compared with the results of aggregated PVP. One can see that for both DM and SFM, the THD values of current and voltage by the aggregated PVP model are greater than values obtained from the detailed PVP model. Moreover, for both aggregated and detailed PVP, the THD of DM is greater than SFM. Hence, for a more precise harmonic analysis, prioritizing the use of DM is recommended.

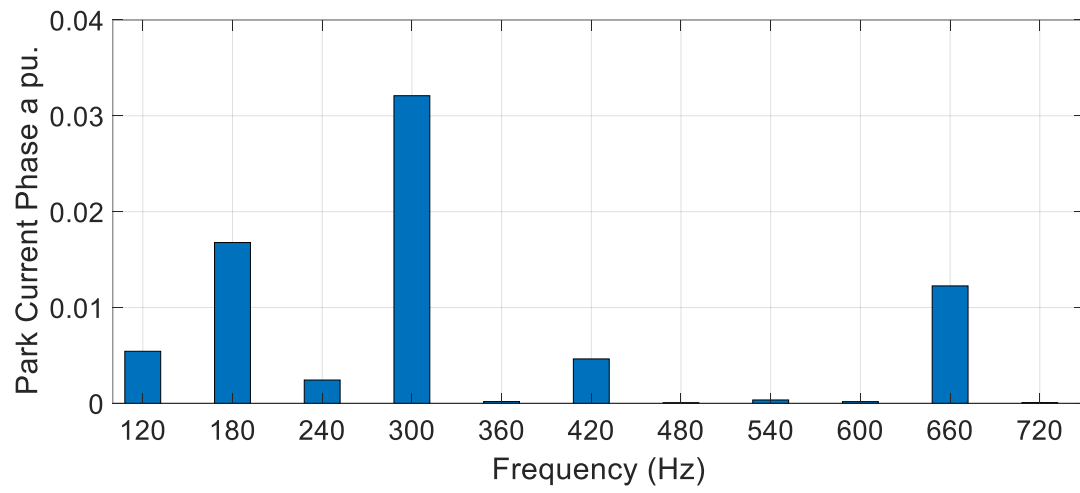


(a)

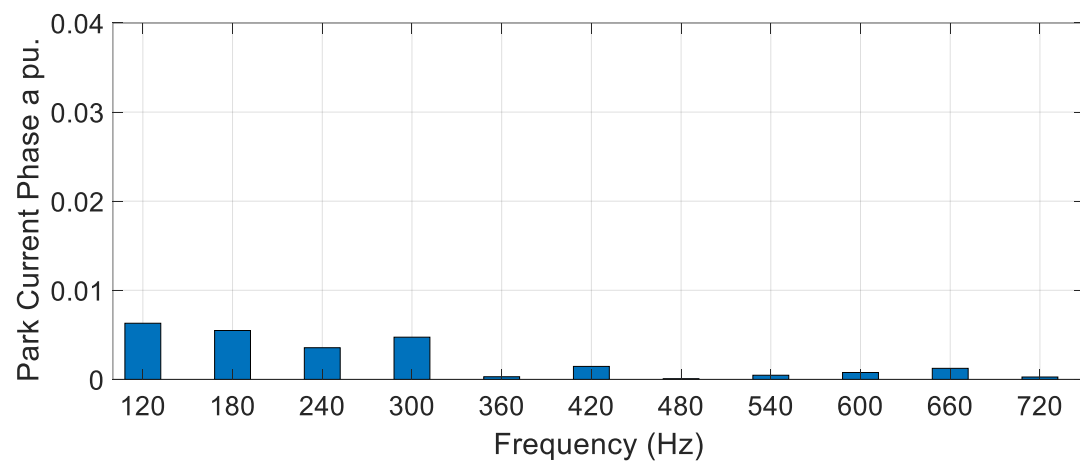


(b)

Figure 5-16 FFT of the PCC voltage phase a a) DM b) SFM



(a)



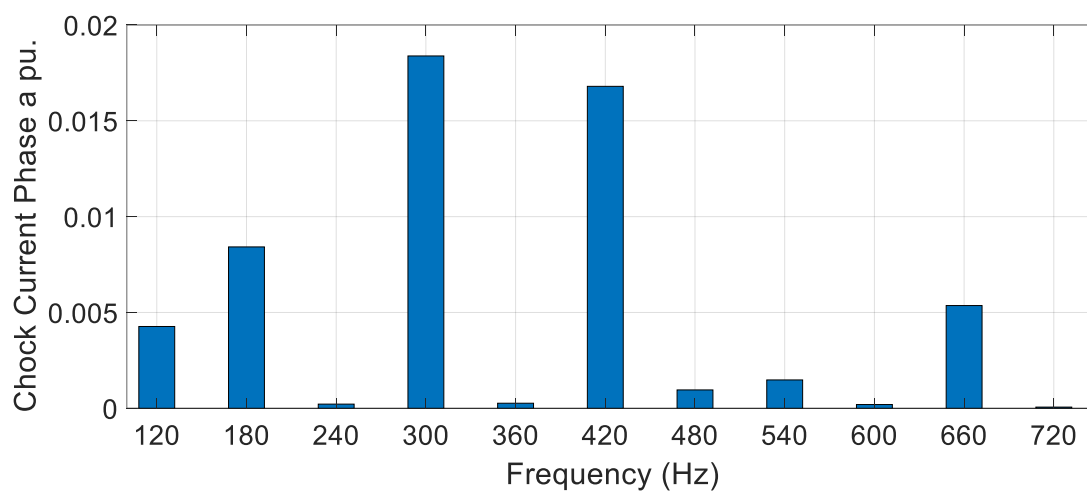
(b)

Figure 5-17 FFT of the park current phase a) DM b) SFM

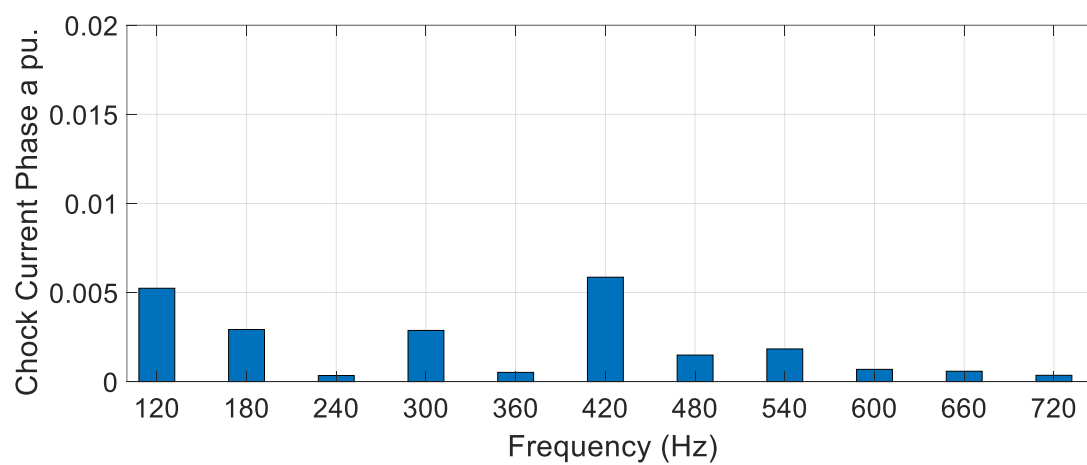
Table 5.3 THD of current and voltage

	Aggregated PV Park		Detailed PV Park	
Model	DM	SFM	DM	SFM
THD PCC Voltage	3.97	0.85	1.38	0.71
THD Park current	3.90	1.075	1.64	0.66

Figure 5-18 shows the harmonic content of the choke current, phase a , for DM, and SFM. The THD of the DM and SFM are summarized in Table 5.4.



(a)



(b)

Figure 5-18 FFT of the choke current phase a a) DM b) SFM

Table 5.4 THD of the choke current

Model	Aggregated PV Park	
	DM	SFM
THD of choke current	5.36	5.2

By comparison of the simulation results summarized in Table 5.3 and Table 5.4, it becomes evident that THD shows an increase from 3.9% to 5.36% when computed from the choke current as opposed to the park current and from 1.07% to 5.2% for the DM and SFM, respectively.

Concluding this chapter, the THD of a DM and SFM for a converter depends on the specific converter topology, operating conditions, and the level of detail included in the model. Generally, a DM provides a more accurate representation of the converter behavior and can capture higher-order harmonics, while a SFM is simpler and computationally more efficient but may not capture all the harmonics accurately. While SFMs can provide a good approximation of the inverter's behavior, they may not capture all the nonlinearities and complexities that affect the THD.

CHAPTER 6 WECC MODEL AND ITS COMPARISON WITH DM, AVM, AND SFM CONVERTER MODELS

6.1 Western Electricity Coordinating Council (WECC) Model

A positive sequence, fundamental frequency model of GE solar PV plants, was proposed in 2010 [127, 128]. The model has been used for the solar plant interaction with the grid in the presence of disturbances. The Western Electricity Coordinating Council (WECC) renewable energy modeling task force proposed a positive sequence generic dynamic model for the units with 10 MVA or higher in [8, 78, 129] and an update in [77] based on recent solar PV tripping events due to system disturbance and Federal Energy Regulatory Commission (FERC) new technical requirements (FERC Order 827 and FERC Order 824) which revealed some weakness of the previous modeling approach. WECC PV model has been validated in [130], using field measured data. However, the performance of controllers has not been considered for validation. Real data from the PV inverter and the PV power plant have been used to validate the WECC generic PV model [131]. Given its significance and widespread adoption among power engineers for voltage stability analysis, the WECC is also included in the comparisons presented in this thesis.

The WECC PVP model includes three main modules which are illustrated in Figure 6-1.

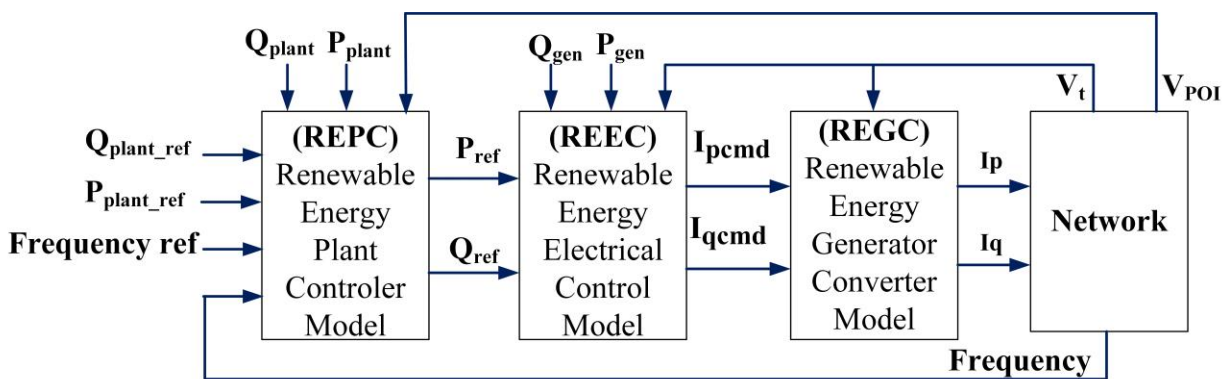


Figure 6-1 WECC PV plant model [132]

The dynamic performance of the inverter interfaced with the grid is represented by the Renewable Energy Generator Converter (REGC) module. The duty of REGC is to receive the real and reactive current commands I_{pcmd} and I_{qcmd} from the Renewable Energy Electrical Controls (REEC) module and to inject real and reactive current components, I_p and I_q , into the grid. The Renewable Energy Plant Control module (REPC) provides the real and reactive power references P_{ref} and Q_{ref} for the REEC module. Then REEC module delivers the real and reactive powers, P_{gen} and Q_{gen} , to the inverter terminal. The voltage at the POI, V_{POI} , plant real power, P_{plant} , plant reactive power, Q_{plant} , and frequency are measured and sent to REPC. Moreover, the plant controller also receives as input the reference values of frequency, $Frequency_{ref}$, and the plant level real and reactive powers, P_{plant_ref} and Q_{plant_ref} [132]. The REGC-A and REGC-C modules are shown in Figure 6-2 and Figure 6-3, respectively. The REGC.A is the first developed model by WECC, which is a current-source model. It is suitable for strength-grid connection points, where the short-circuit ratio (SCR) of the point of interconnection may be higher than 5. The REGC.C is a new model, which is also implemented in EMTP. This is a voltage source model that combines a generic representation of the PLL and inner-current control loops of the converter. The model efficacy has been shown using a version developed by EPRI for very low SCR [133]. The REEC-D and REPC-A are illustrated in Figure 6-4, and Figure 6-5, respectively.

The WECC models were originally crafted for transmission planning studies encompassing intricate networks and an extensive array of generators, loads, and other dynamic elements. The primary aim is to evaluate the dynamic behavior of the system, particularly its ability to recover after grid-side disturbances like transmission-level faults. Within this framework, WECC employs positive-sequence dynamic models that effectively capture recovery dynamics.

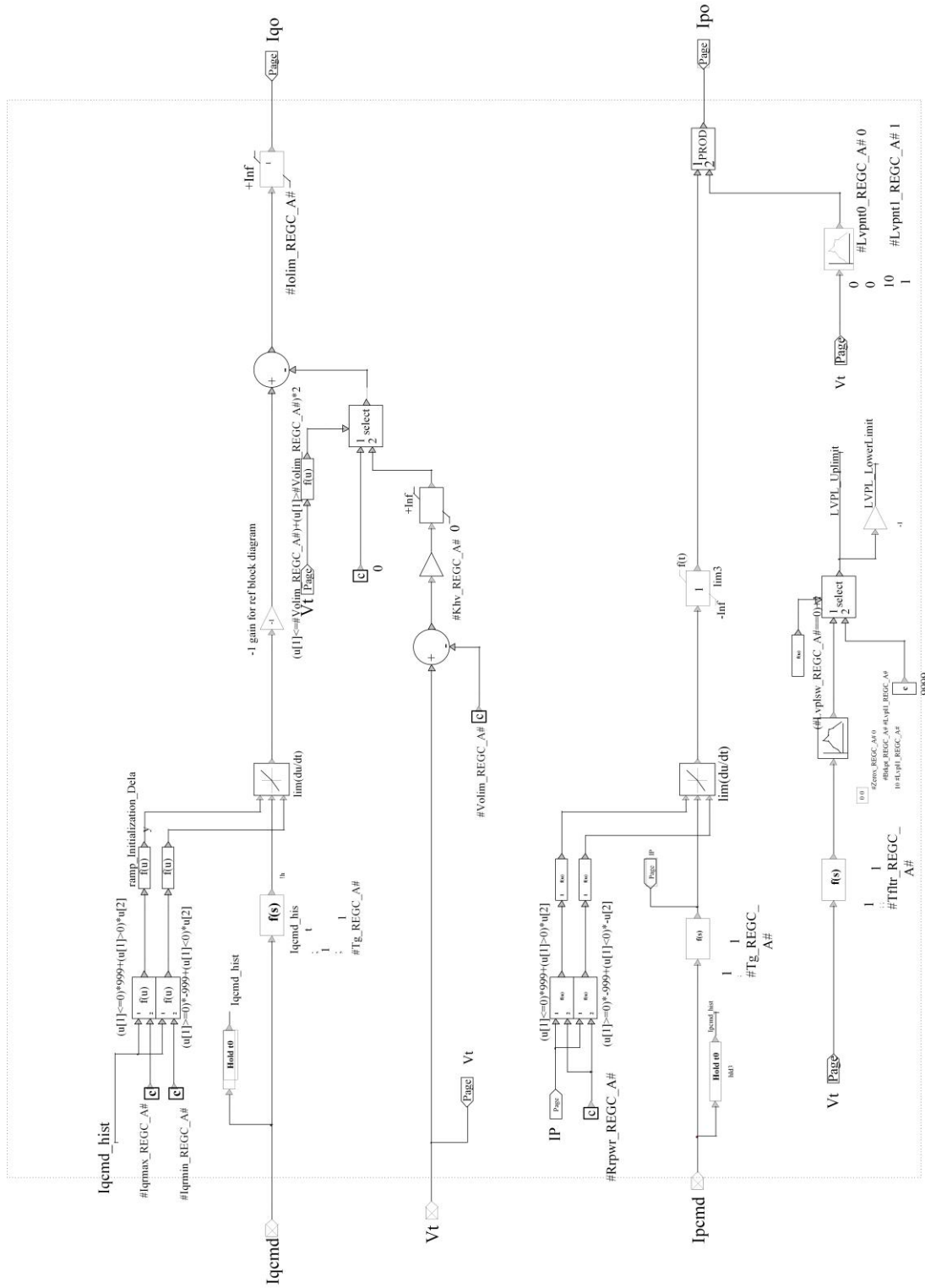


Figure 6-2 REGC-A module

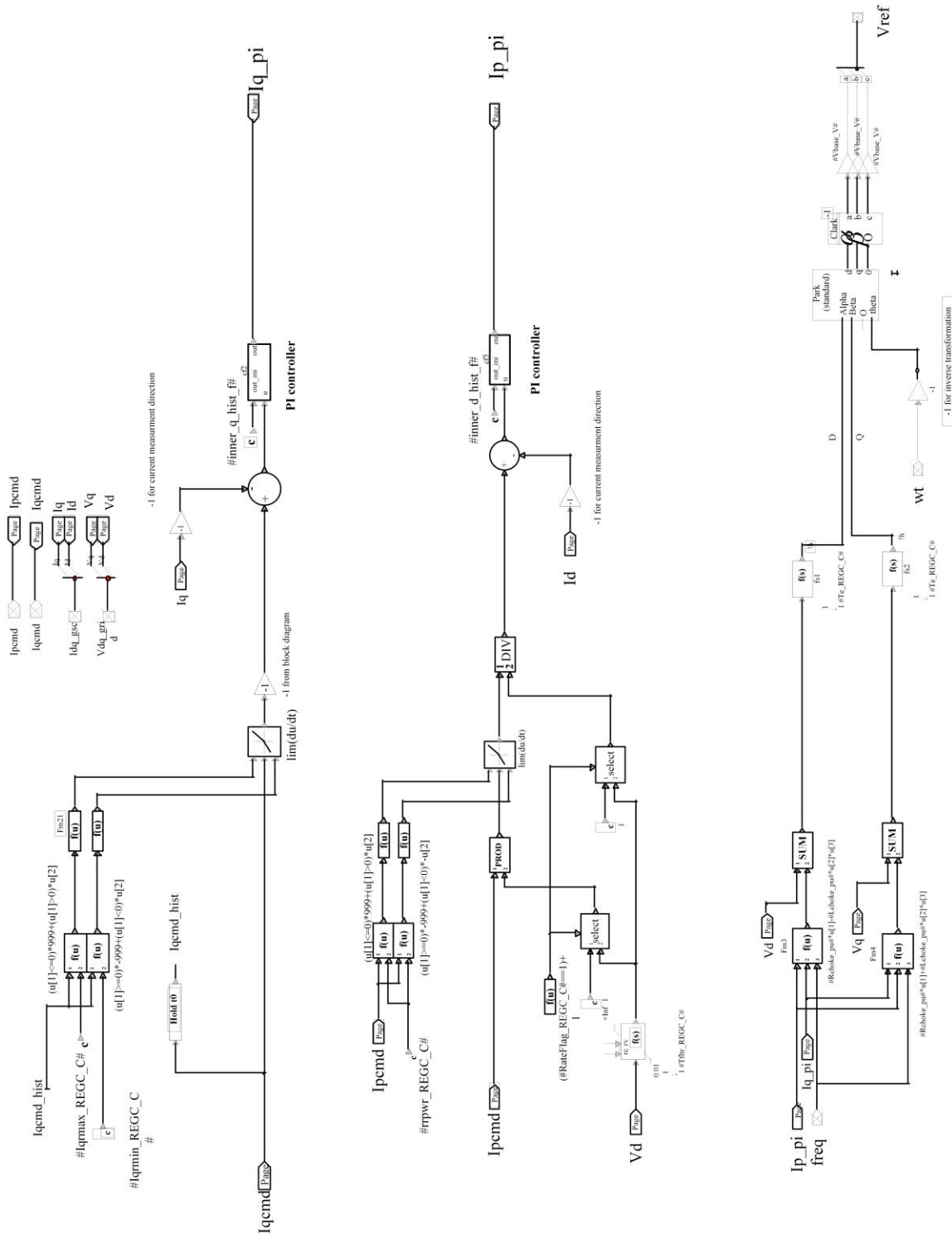


Figure 6-3 REGC-C module

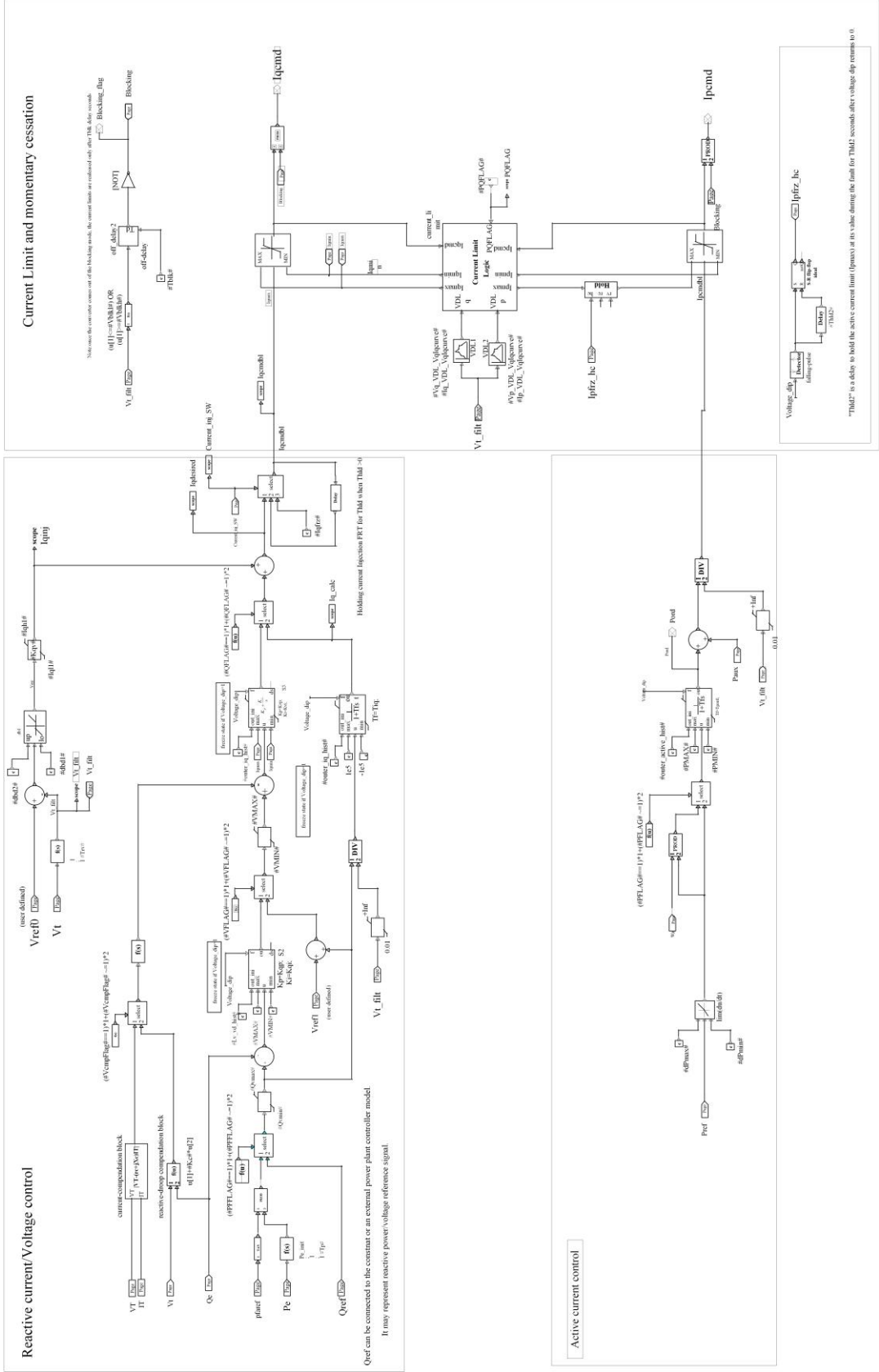
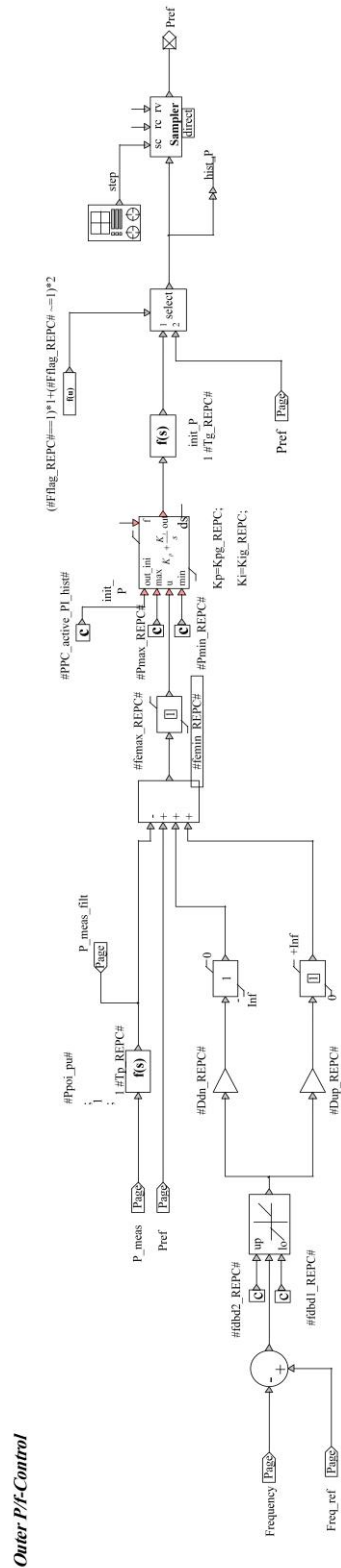


Figure 6-4 REEC-D Modul



In this section, the test network used in Chapter 5 (Figure 5-1) is used for the 3-phase fault analysis at Bus3 and Bus1 in separate studies. Different combinations of the WECC converter and control module are compared with DM, AMV, and SFM results presented in chapter 5. The different models used in the simulations are summarized in Table 6.1.

Table 6.1 The type of converter model and control system used in the simulation

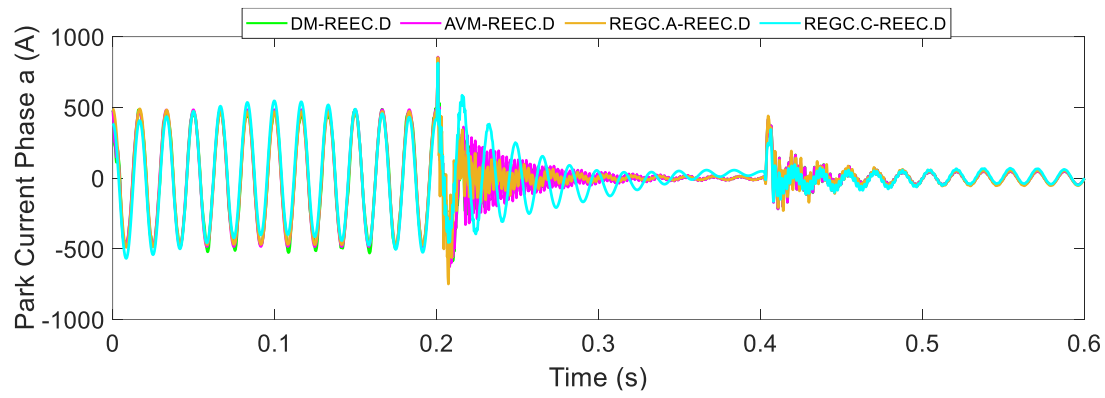
Model	Complete Model Name	Type of Converter Model	Type of Control System
DM	Detailed Model	Detailed	Detailed
AVM	Average Value Model	Average Value	Detailed
SFM	Switching Function Model	Switching Function	Detailed
DM-REEC.D	Detailed model-Renewable energy electrical control version D	Detailed	REEC.D
AVM-REEC.D	Average Value Model -Renewable energy electrical control version D	Average Value	REEC.D
REGC.A-REEC.D	Renewable energy generator conveter module version A - Renewable energy electrical control module version D	REGC.A	REEC.D
REGC.C-REEC.D	Renewable energy generator conveter module version C - Renewable energy electrical control module version D	REGC.C	REEC.D

6.2 3-Phase fault at BUS3

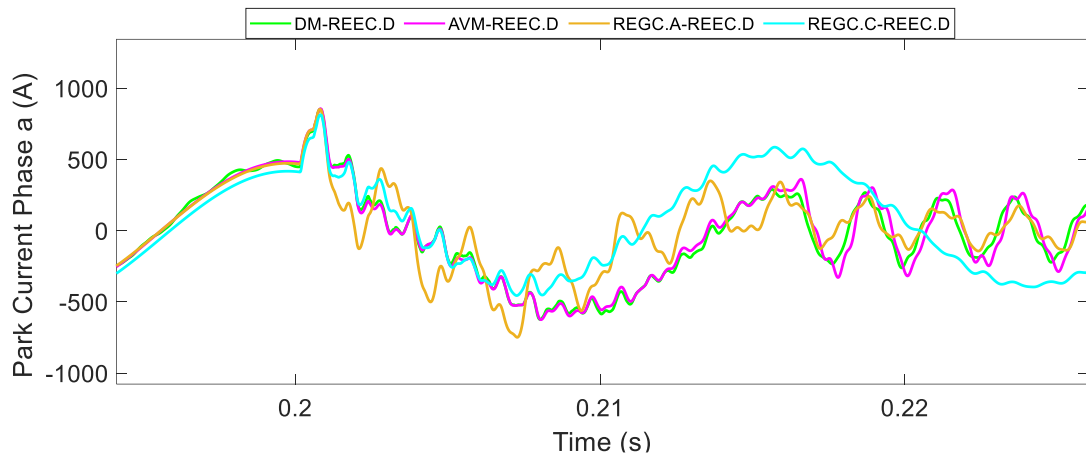
In this section, a three-phase fault occurs in BUS3 at $t = 0.2$ s and clears at $t = 0.4$ s. Figure 6-6 shows the current, phase a , delivered by the PVP, for the different combinations of the converter models and WECC subsystems model. For the converter model, the DM, AVM, and versions A and C of the renewable energy generator converter model (REGC.A and REGC.C) are used. For example, in the DM-REEC.D, the detailed model of converter and the REEC.D model of the control system are used. Also, in the REGC.C-REEC.D, REGC.C module is used for the converter model, and REEC.D is employed for the control system.

Moreover, version D of the renewable energy electrical control system (REEC.D) is used for the comparison. One can see that the different model results shown in Figure 6-6 are close to each other except around the fault occurrence at $t = 0.2$ s. Moreover, since the control is not fast enough it takes time for the current to return the values before than fault.

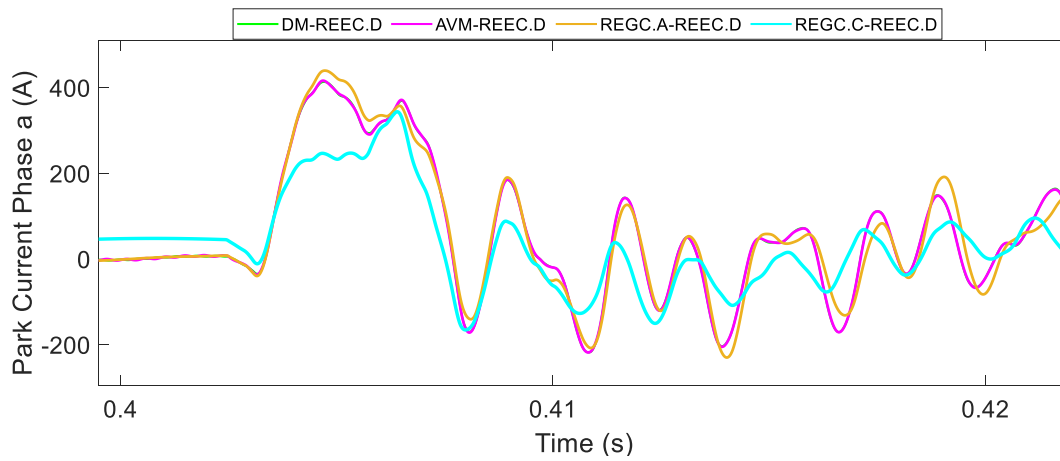
In Figure 6-7, for a better comparison, the results of simulations for the different converter models (DM, AVM, SFM) provided in the Chapter 5, are added to the simulation results depicted in Figure 6-6. It should be noticed that in Figure 6-7, the control system for the three first simulations (DM, AVM, SFM) is the detailed control system, and for the last four simulations is REEC.D proposed by WECC.



(a)

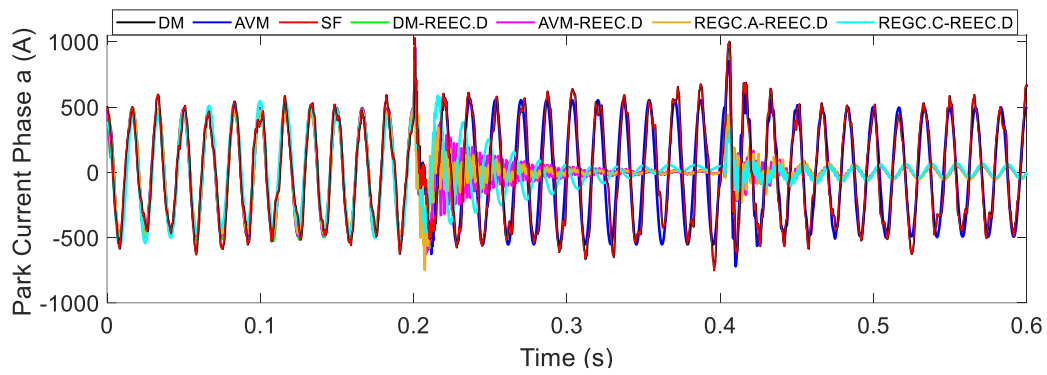


(b)

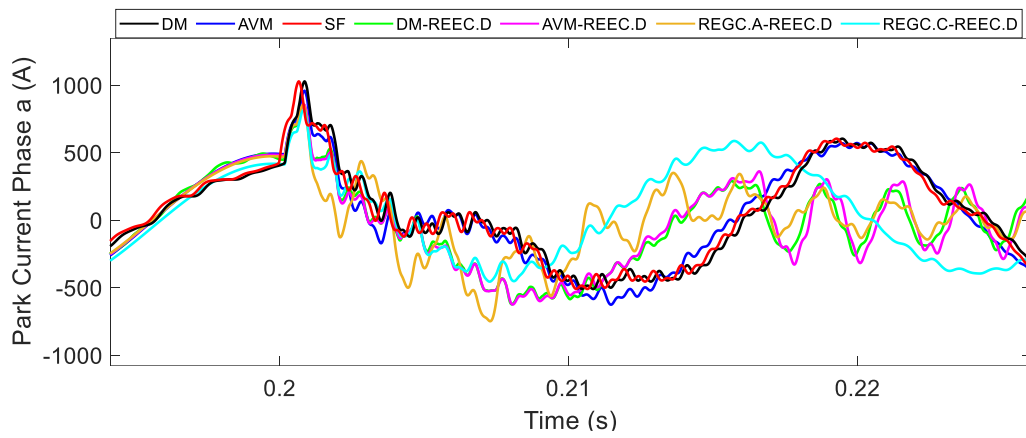


(c)

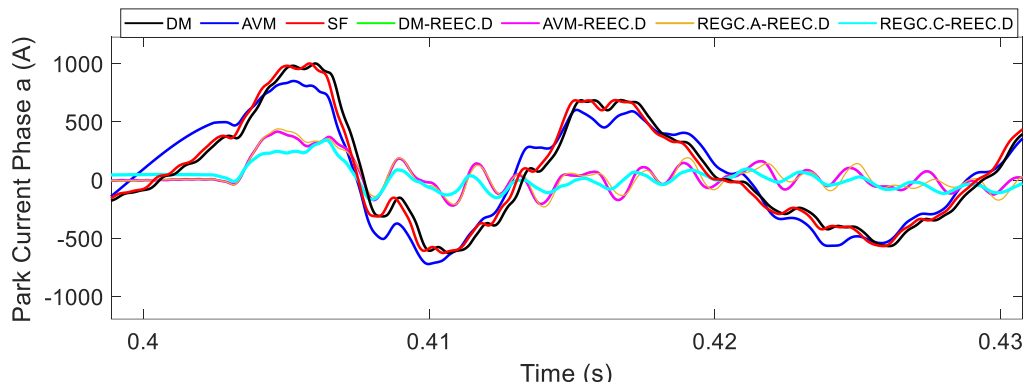
Figure 6-6 Comparison of PVP current phase a, results from different PV park models for the 3-phase fault at BUS3 a) Whole simulation time b) zoomed around $t = 0.2$ s (fault occurring) c) zoomed around $t = 0.4$ s (fault clearing)



(a)



(b)



(c)

Figure 6-7 Comparison of PVP current phase a, results from different PV park models for the 3-phase fault at BUS3 a) Whole simulation time b) zoomed around $t = 0.2$ s (fault occurring) c) zoomed around $t = 0.4$ s (fault clearing)

From Figure 6-7, one can conclude that the results of DM, AVM, and SFM, with the detailed control system, are very close to each other (as it has been illustrated in Chapter 3, Figure 5-4). However, they do not agree with the last four simulation results using the REEC.D control system during the fault and after the fault clearing (although they are close in steady state condition before the fault).

Figure 6-8 and Figure 6-9 show the comparison of the PCC voltage phase a , obtained from different PV park models when a 3-phase fault occurs at BUS3. In Figure 6-9, for a better comparison, the results of simulations for the different converter models (DM, AVM, SFM) provided in the chapter 3, are added to the simulation results depicted in Figure 6-8. It should be noticed that in Figure 6-9, the control system for the three first simulations (DM, AVM, SFM) is the detailed control system, and for the last four simulations is REEC.D proposed by WECC. One can see that before the fault occurs, the PCC voltage waveforms almost coincide with each other. However, after the fault and between $t = 0.2$ s and $t = 0.3$ s, they do not match.

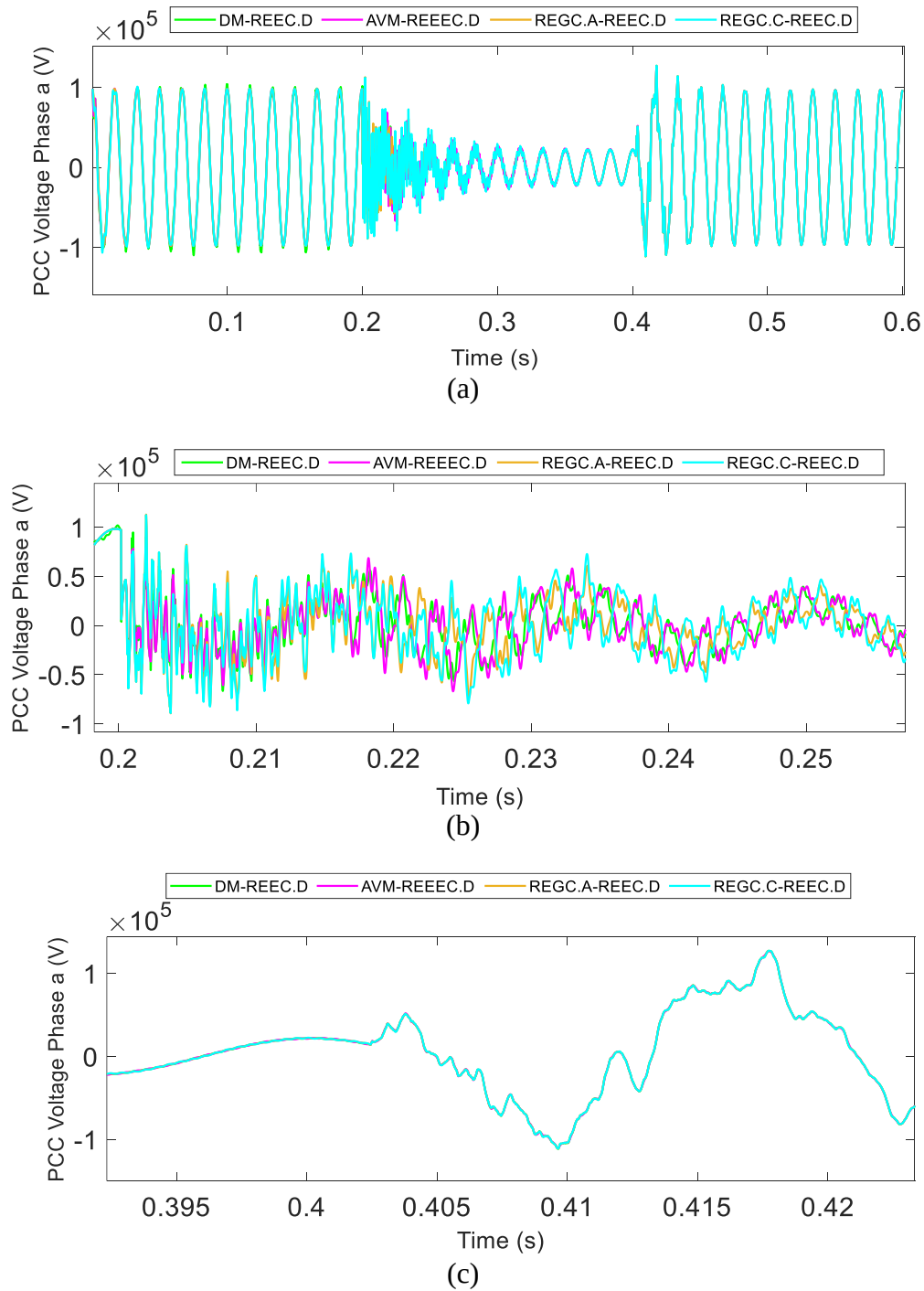


Figure 6-8 Comparison of PCC voltage results from different PV park models for the 3-phase fault at BUS3 a) Whole simulation time b) zoomed around $t = 0.2$ s (fault occurring) c) zoomed around $t = 0.4$ s (fault clearing)

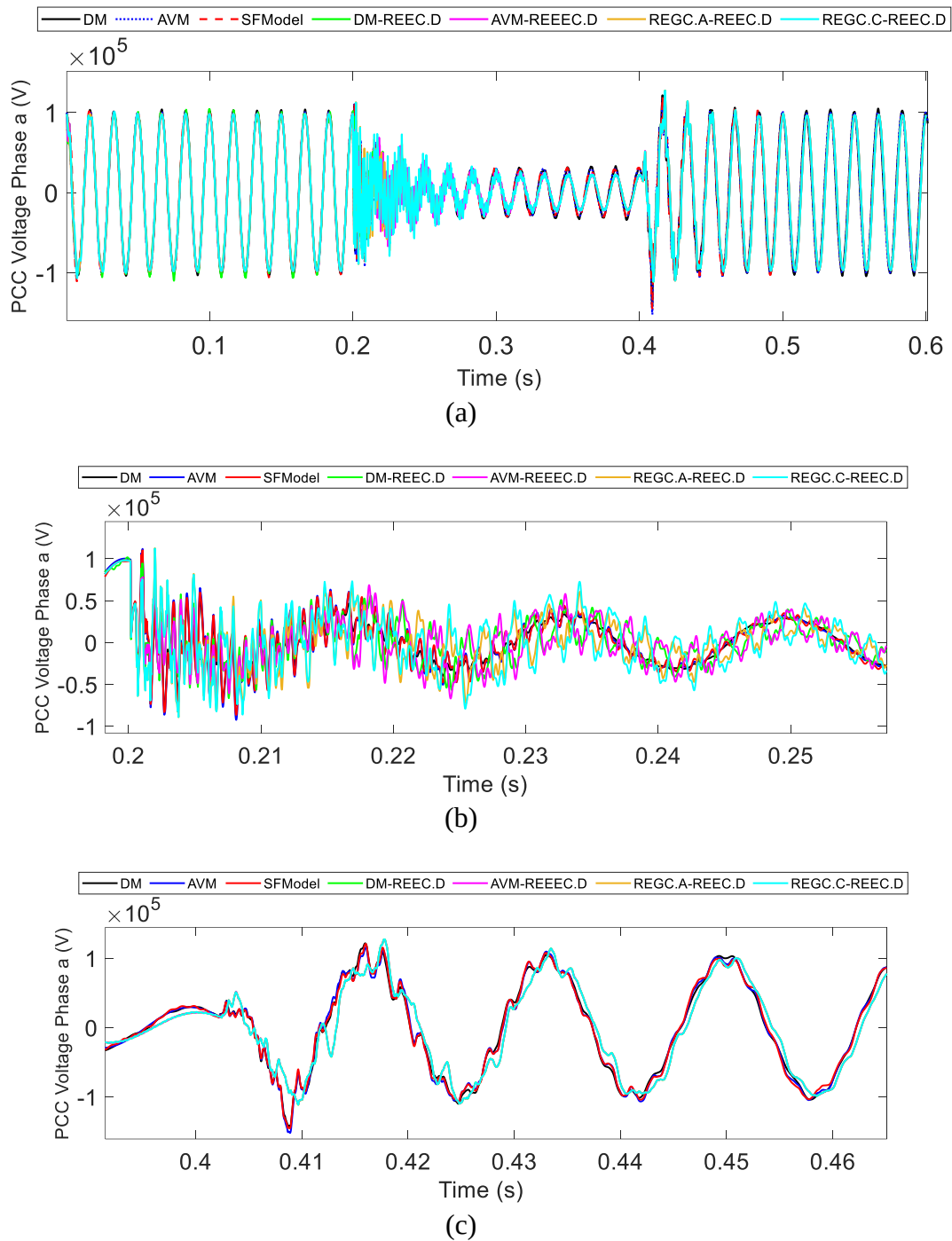
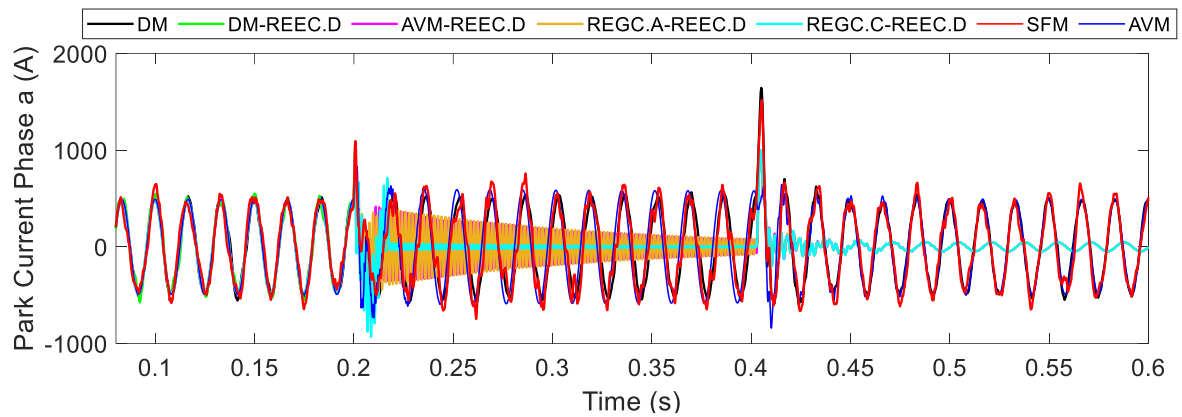


Figure 6-9 Comparison of PCC voltage results from different PVP models for the 3-phase fault at BUS3 a) Whole simulation time b) zoomed around $t = 0.2$ s (fault occurring) c) zoomed around $t = 0.4$ s (fault clearing)

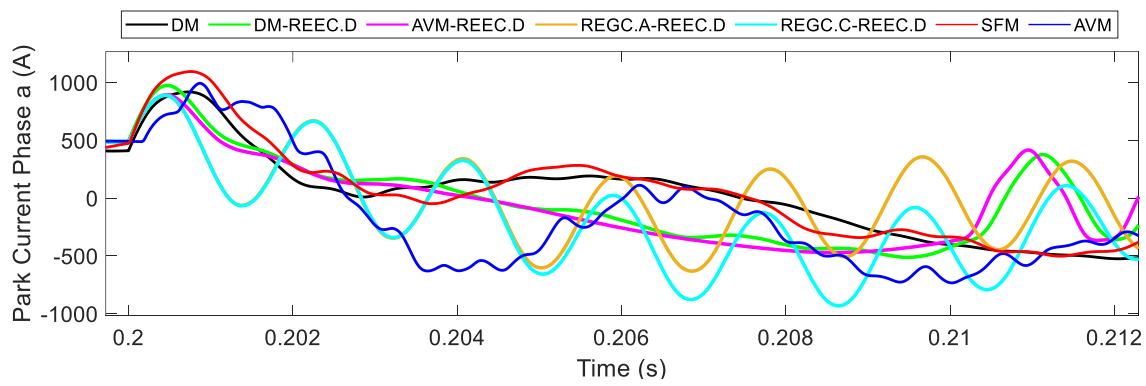
6.3 3-Phase fault at BUS 1

Figure 6-10 illustrates the PVP current phase a , achieved from the different PVP, and converter models, when a 3-phase fault occurs at BUS1. In Figure 6-10, one can see that in the steady state region before the fault, the results from different combination of WECC modules are close to DM. However, during the fault and even after clearing the fault, they are far from the DM. Especially the REGC.A-REEC.D and REGC.C-REEC.D models' response is very different from the others during the fault. The oscillation frequency of REGC.A-REEC.D and REGC.C-REEC.D is significantly higher compared to other models. Additionally, during the fault the amplitude of the REGC.A-REEC.D model surpasses that of the REGC.C-REEC.D model by a considerable margin. Figure 6-10b and Figure 6-10c shows the zoomed area around the $t = 0.2$ s and $t = 0.4$ s. The SFM and AVM results also are depicted to compare with the WECC model results. It can be observed that right after the fault (Figure 6-10b) the SFM has better accuracy than AVM and WECC models and, while the SFM is close to DM, the other models are distancing from the DM model. After clearing the fault at $t = 0.4$ s (Figure 6-10c) the simulation results of WECC modules are close to each other. However, there is difference between their performance and DM. It worth to mention that SFM result after clearing the fault is also close to DM.

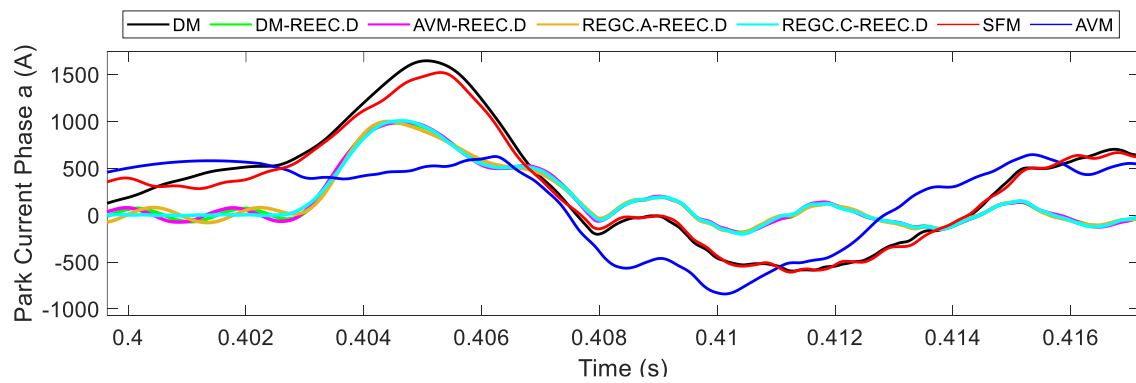
Figure 6-11 depicts the PCC voltage phase a , obtained from the different PV park, and converter models when a 3-phase fault occurs at BUS1. One can see the different WECC model results for the PCC voltage are very close to each other. Moreover, the WECC model results are close to DM results. It can be inferred that the PCC voltage of different models is relatively unaffected by faults occurring.



(a)

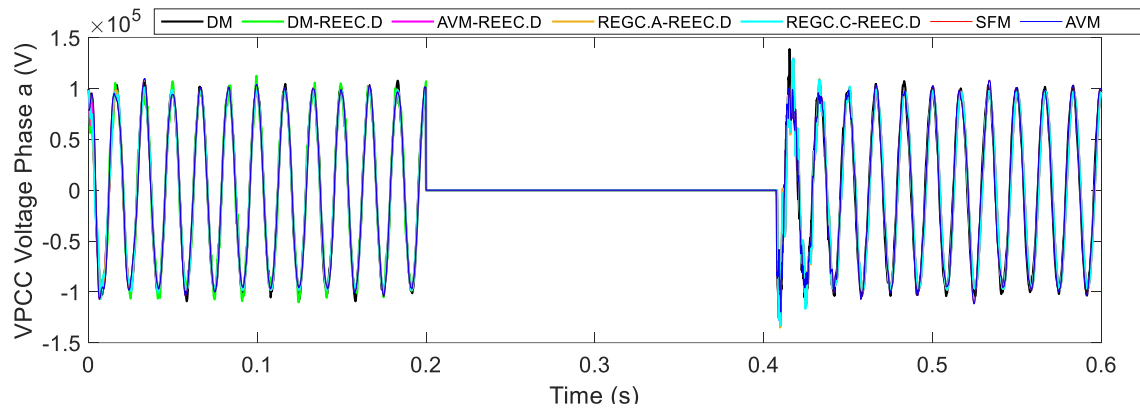


(b)

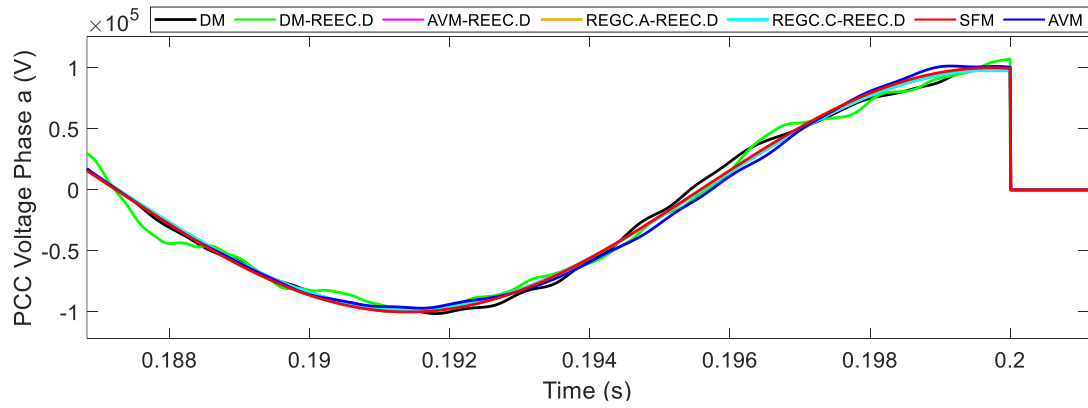


(c)

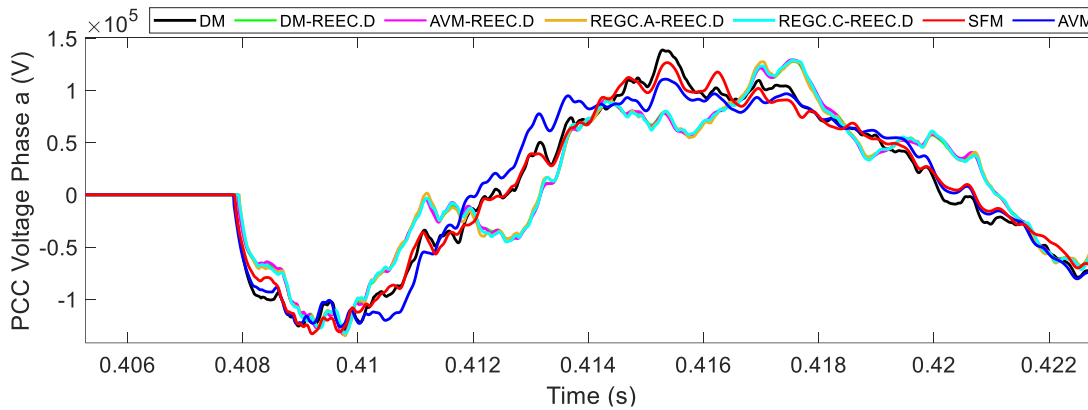
Figure 6-10 Comparison of PV park current phase a, results from different PVP models for the 3-phase fault at BUS1 a) Whole simulation time b) zoomed around $t = 0.2$ s (fault occurring) c) zoomed around $t = 0.4$ s (fault clearing)



(a)



(b)



(c)

Figure 6-11 Comparison of PCC voltage phase a, results from different PVP models for the 3-phase fault at BUS1 a) Whole simulation time b) zoomed around $t = 0.2$ s (fault occurring) c) zoomed around $t = 0.4$ s (fault clearing)

CHAPTER 7 CONCLUSION

This thesis has reviewed three different types of grid-side converter models, i.e., DM, AVM, and SFM, used in PV parks for EMT studies. The simulation results of these models have been compared in terms of accuracy and computational efficiency. As expected, the DM is more accurate than the AVM and SFM; however, it involves intense computational burden. Moreover, it has been shown that in normal operation condition of converter, the results achieved from AVM and SFM are close to each other. In blocking mode condition, on the other hand, the SFM result is more accurate than AVM.

Also, the CPU times by these three models are compared when adopting either an aggregated or a detailed model PVP. In addition, the voltage, and current harmonic contents of three models are compared with each other. As observed in Chapter 5, a delicate balance exists between accuracy and simulation time among the three models (DM, AVM, SFM). DM stands out as the most accurate option but demands a significant amount of time for simulations. AVM, on the other hand, excels in terms of simulation efficiency but tends to overlook fast transients. SFM strikes a compromise between accuracy and efficiency, offering higher accuracy than AVM but requiring more time for simulation.

Furthermore, both DM and SFM models can furnish valuable insights into the harmonic characteristics of voltage and current waveforms, whereas the AVM model does not yield any information on harmonics.

Besides the comparison of the three above mentioned models, the positive sequence upper control model proposed by WECC has been discussed in Chapter 6. The simulation results obtained from different modules combination of the WECC model have been compared with simulation results achieved from different converter models discussed in Chapter 5. It has been shown that in steady state conditions the results of WECC model with REEC.D control system is close to results obtained from DM, AVM, and SFM that have a detailed control system. However, during the fault and after the fault clearing the simulation results do not match. It can be concluded that the WECC model does not facilitate a detailed representation of extremely rapid control actions or responses to unbalanced disturbances. Nevertheless, it could serve as a suitable model for voltage stability studies.

The research work in this thesis remains preliminary and more analysis is required for more generic conclusions.

7.1 Directions for Future Work

The research work conducted in this thesis should be viewed as a first step and further research is required for studying and concluding on different model types for PV applications. The research should continue.

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