CHAPTER 2
SYSTEM MODELLING

2.1 Introduction

The analysis, operation and design of complex ac-dc systems require extensive simulation resources that are accurate and reliable. Analog simulators, long used for studying such systems, have reached their physical limits due to the increasing complexity of modern systems. Currently, there are several industrial grade digital time-domain simulation tools available for modeling ac-dc power systems. Among them, some have the added advantages of dealing with power electronics apparatus and controls with more accuracy and efficiency. PSCAD/EMTDC and PSB/SIMULINK are such two simulators that are being increasingly used in the industry as well as in the universities. Both programs allow the user to construct schematic diagram of electrical networks, run the simulation, and produce the results in a user-friendly graphical environment. Furthermore, several real-time digital simulators use models or the graphical front-end that are similar to PSCAD/EMTDC and PSB/SIMULINK.

PSCAD/EMTDC is a powerful time-domain transient simulator for simulating power systems and its controls. It uses graphical user interface to sketch virtually any electrical equipment and provide a fast and flexible solution. PSCAD/EMTDC represents and solves the differential equations of the entire power system including both electromagnetic and electromechanical systems and its control in the time domain [10]. It employs the well-known nodal analysis technique together with trapezoidal integration rule with fixed integration time-step. It also uses interpolation technique with instantaneous switching to represent the structural changes of the system.

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behavior of electrical networks. Its graphical user interface enables all aspects of the simulation to be conducted within a single integrated environment including circuit assembly, run-time control, analysis of results, and reporting. Its comprehensive library of models supports most ac and dc power plant components and controls in such a way
that FACTS, custom power, and HVDC systems can be modelled with speed and precision. It provides a powerful resource for assessing the impact of new power technologies in the power network.

Simplicity of use is one of the outstanding features of PSCAD/EMTDC. It has great many modelling capabilities and highly complex algorithms and methods are transparent to the user, leaving him free to concentrate his efforts on the analysis of results rather than on mathematical modelling. For the purpose of system assembling, the user can either use the large base of built-in components available in PSCAD/EMTDC or to its own user-defined models.

As the idea of simultaneous ac-dc transmission is a new concept, the well-recognized PSCAD/EMTDC package has been employed for the study. The system components are modelled in PSCAD/EMTDC as suggested in references [1,7,10].

2.2 Salient Pole / Round Rotor Synchronous Machine Modelling in EMTD /PSCAD

The modelling of synchronous machine is based on Park’s transformation from phase to $dq_0$ quantities. The general equivalent circuit for the synchronous machine is as shown in Fig. 2.1. A second damper winding on the $q$-axis is included in this model and hence it can also be used as a round rotor machine to model steam turbine generators. This model can also be suitable for studying sub-synchronous resonance (SSR) problems as well.

This model operates in the generator mode so that a positive real power indicates electrical power leaving the machine, and a positive mechanical torque indicates mechanical power entering the machine. A positive reactive power indicates that the machine is supplying reactive power indicating it is overexcited.

The generalized machine model transforms the stator windings into equivalent commutator windings, using the $dq_0$ transformation as follows:

\[
\begin{bmatrix}
U_d \\
U_q \\
U_0
\end{bmatrix} =
\begin{bmatrix}
\cos(\theta) & \cos(\theta - 120^\circ) & \cos(\theta - 240^\circ) \\
\sin(\theta) & \sin(\theta - 120^\circ) & \sin(\theta - 240^\circ) \\
1/2 & 1/2 & 1/2
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]  
(2.1)
Supporting subroutines are included in the machine model library for calculating the equivalent circuit parameters of a synchronous machine from commonly supplied data.

The d-axis equivalent circuit for the generalized machine is shown in Fig. 2.2, and Fig. 2.3 illustrates the flux paths associated with various d-axis inductances.

By inspecting Fig. 2.2 and 2.3, the following equations can be written:

\[
\begin{bmatrix}
U_{d1} - \nu \Psi_d - R_1 i_{d1} \\
U_{d2} - R_{2d} i_{d2} \\
U_{d3} - R_{3d} i_{d3}
\end{bmatrix} = L_d \frac{di}{dt}
\begin{bmatrix}
i_{d1} \\
i_{d2} \\
i_{d3}
\end{bmatrix}
\]  
(2.2)

Where,

\[
L_d = \begin{bmatrix}
L_{dM} + L_1 & L_{dM} & L_{dM} \\
L_{dM} & L_{dM} + L_{2d} & L_{dM}
\end{bmatrix}
\]  
(2.3)

\[
\Psi_d = L_1 i_{q1} + L_{dM} (i_{d1} + i_{d2} + i_{d3})
\]  
(2.4)

\[
\nu = \frac{d\theta}{dt}
\]  
(2.5)

Similar equations can be written for the q-axis except the speed voltage term, \(\nu\Psi_d\), is positive,

and:

\[
\Psi_q = L_1 i_{q1} + L_{dM} (i_{d1} + i_{d2} + i_{d3})
\]  
(2.6)

Inversion of equation (2.2) gives the standard state variable form \(X = AX + BU\) with state vector \(X\) consist of the currents, and the input vector \(U\) that of applied voltages.

That is:

\[
\frac{d}{dt}\begin{bmatrix}
i_{d1} \\
i_{d2} \\
i_{d3}
\end{bmatrix} = L_d^{-1} \begin{bmatrix}
-\nu \Psi_d - R_1 i_{d1} \\
- R_{2d} i_{d2} \\
- R_{3d} i_{d3}
\end{bmatrix} + L_d^{-1} \frac{d}{dt}\begin{bmatrix}
U_{d1} \\
U_{d2} \\
U_{d3}
\end{bmatrix}
\]  
(2.7)

\[
\frac{d}{dt}\begin{bmatrix}
i_{q1} \\
i_{q2} \\
i_{q3}
\end{bmatrix} = L_q^{-1} \begin{bmatrix}
\nu \Psi_q - R_1 i_{q1} \\
- R_{2d} i_{q2} \\
- R_{3d} i_{q3}
\end{bmatrix} + L_q^{-1} \frac{d}{dt}\begin{bmatrix}
U_{q1} \\
U_{q2} \\
U_{q3}
\end{bmatrix}
\]  
(2.8)
Fig. 2.1. Conceptual Diagram of the Three-Phase and d q Windings

Note: All quantities shown in Fig. 2.1 are in per unit.

Where,

- k- Amortisseur windings
- f- Field windings
- abc- Stator windings
- d- Direct-Axis (d-axis) windings
- q- Quadrature-Axis (q-axis) windings
In the above form, equations (2.7) and (2.8) are particularly easy to integrate. The equations are solved using trapezoidal integration to obtain the currents. The torque equation is given as:

\[ T = \Psi_q \cdot i_d - \Psi_d \cdot i_q \]  \( (2.9) \)

and the mechanical dynamic equation for motor operation is:

\[ \frac{dv}{dt} = \frac{T - T_{\text{MECH}} - D \cdot v}{J} \]  \( (2.10) \)

Referring to Fig. 2.2 and Fig. 2.3, the d-axis voltage \( U_{D2} \) and current \( I_{D2} \) are the field voltage and current, respectively. The damper circuit consists of parameters \( L_{3D} \) and \( R_{3D} \)
with \( U_{D3} = 0 \). The additional inductance \( L_{23D} \) accounts for the mutual flux, which links only the damper and field windings and not the stator winding. The inclusion of such flux is necessary for accurate representation of transient currents in the rotor circuits. The saturation effect only on \( L_{MD} \) is considered in this machine and is based on the magnetizing current,

\[
i_{MD} = i_{D1} + i_{D2} + i_{D3}
\]  

(2.11)

The matrix \( L^{-1} \) is recalculated each time there is a change in the saturation factor.

### 2.2.1 The Per-Unit System

The per-unit system is based on the preferred system indicated in [1,10]. The base value of voltage and current in the three-phase system is the RMS phase voltage \( V_{a0} \), and RMS phase current \( i_{a0} \). The same voltage base is used in the \( dq0 \) system but the base current is changed to \( 3/2 i_{a0} \). The \( dq0 \) transformation in per unit for the voltage or current is given in equation (2.1). The inverse transform is:

\[
\begin{bmatrix}
i_d \\
i_q \\
i_0
\end{bmatrix} = 
\begin{bmatrix}
\cos(\theta) & \sin(\theta) & 1 \\
\cos(\theta - 120^\circ) & \sin(\theta - 120^\circ) & 1 \\
\cos(\theta - 240^\circ) & \sin(\theta - 240^\circ) & 1 
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]  

(2.12)

Note that unit current in the d-winding produces the same total MMF as unit currents acting in a balanced fashion in the abc-windings. Unit currents in the different circuits should produce the same physical effect. In both systems base power is:

\[
P_0 = 3 \cdot V_{a0} \cdot i_{a0}
\]  

(2.13)

The associated bases are:

\[
\omega_0 = \text{Rated frequency in radians}
\]

\[
t_0 = \frac{1}{\omega_0}
\]

\[
L = x
\]

\[
\Psi_0 = \frac{V_{a0}}{\omega_0}
\]  

Base flux linkage
\[ \nu_o = \frac{\omega_o}{PolePairs} \quad \text{Base mechanical Speed} \]

\[ \theta_m = \frac{\theta}{PolePairs} \quad \text{Mechanical angle} \]

The impedances are given in per unit. The input voltages are divided by \( V_{a0} \) and the incremental time \( \Delta t \) is multiplied by \( \omega_o \) to provide a per unit incremental time. The per-unit current is converted to output current by multiplying it by \( i_{a0} \) after transformation from the two-axis system.

Care should be taken with the following quantities:

Utilities often specify one per unit field current and voltages as that which produces rated open circuit voltage on the air-gap line (this implies unit power loss in the field circuit). The per unit field current \( i_{D2} \) must be multiplied by \( X_{MD0} \) and then divided by \( \sqrt{2} \) in order to convert it to the value of field current used in the utility system. The value of the field voltage is multiplied by \( R_F/X_{MD0} \) to give the correct per unit value of \( U_{D2} \).

### 2.2.2 Machine Interface to EMTDC

The machine models represent the machine as a Norton current source into the EMTDC network. This approach uses the terminal voltages to calculate the currents to be injected.

Fig. 2.4 shows a synchronous machine model interfaced to the EMTDC program. The synchronous machine model makes use of the phase voltages calculated by EMTDC to update the injected currents into EMTDC. It is also shown in this figure that multiplying the phase currents by an integer \( N \) simulates (from the system point of view) \( N \) identical machines operating coherently into the AC system.
Terminating Resistance

It is important to note that representing machines as a Norton current source can have drawbacks. For instance, each machine must be computationally 'far' from other machines for stable operation. In the past, this was usually achieved by separating subsystems containing machines by distributed transmission lines (which are essentially time delays). Since the machine was represented by a simple current source (which was dependent on voltages from the previous time step), any sudden change in voltage would cause a current response only in the next time step. Thus, for the previous time step, the machine looked like an open circuit and spurious spikes appeared on the machine terminal voltage. The cumulative effect of many machines causing this error simultaneously in the same subsystem was proven to be de-stabilizing (computationally).

It was found that when the machine neared open circuit conditions a smaller time step was required to maintain computational stability. Alternatively a small capacitance or large resistance could be placed at the machine terminals to ground to prevent the machine from being totally open-circuited. Although the physical meaning of parasitic
capacitance or leakage resistance could be applied to these elements, it was not a satisfactory solution.

This idea led to the concept of terminating the machine to the network through a terminating 'characteristic impedance' as shown in Fig. 2.5. The effect of this added impedance is then compensated (corrected) by injecting appropriate current adjacent to it.

Using this technique, the machine model behavior has been uniformly good. It essentially combines the compensation-based model and the non-compensated model, while eliminating the restriction of adjacent machines and the necessity of calculating the network Thevenin equivalent circuit.

![Fig. 2.5. Interface with terminating resistance.](image)

Where,

\[ l_c(t) = \frac{V_c(t - \Delta t)}{Z''} \]

Compensating current

\[ l_m(t) = \]

Calculated machine current

\[ Z'' = \frac{2 \cdot L''}{N \cdot \Delta t} \]

Terminating 'characteristic impedance'

The impedance \( Z'' \) is calculated where \( L'' \) is the 'characteristic inductance' of the machine, \( N \) is the number of coherent machines in parallel and \( \Delta t \) is the EMTDC time step. This resistance is placed from each node of the machine terminal to ground within the EMTDC network. Instead of injecting the calculated machine current \( l_m(t) \), a
compensated current $I_m(t) + I_c(t)$ is injected, where $V(t - \Delta t)$ is the terminal voltage in the previous time-step. Thus, the actual current injected into the network is,

$$I_{na} = I_m(t) + \frac{V_c(t - \Delta t) - V_c(t)}{Z''} \quad (2.14)$$

$Z''$ is usually quite large, due to the $\Delta t$ in the denominator. Also, for a small time step $V(t - \Delta t) = V(t)$, and thus $I_{na}(t) = I_m(t)$, and the error introduced vanishes in the limit with a small $\Delta t$. However, for a sudden voltage change, as $I_m(t) + I_c(t)$ is not calculated until the next time step, the network sees the impedance $Z''$ for this instant (instead of the open circuit discussed earlier). This is exactly the instantaneous impedance it would have seen, had the machine been represented in the EMTDC program main matrix. Therefore, the network current calculated in this instant is more accurate, and the spurious spikes discussed earlier do not arise. Thus, this concept of terminating the machine with its 'characteristic impedance and then compensating it by current injection, is a convenient way for assuring accurate solutions.

### 2.2.3 Mechanical and Electrical Control

As shown in Fig.2.4, control blocks used to simulate the excitation and governor systems of the synchronous machine need also to be modelled. These control systems are not included internally in the machine model, so they must be interfaced through external connections.

The exciter and governor systems can either be built using standard control system building blocks (available in the CSMF section of the PSCAD Master Library) or standard exciter and governor models available may be used. Following sections briefly describe the general theory behind them.
2.2.3.1 Exciters

Exciters are externally interfaced to the machine models through external signal connections. Since the exciter models exist as separate components, parameters can be freely selected and adjusted by the user.

Reference [1], published by the IEEE, categorizes exciters into three different types:

(i) Type DC excitation systems utilize a DC generator with a commutator as the source of excitation system power

(ii) Type AC excitation systems use an alternator, and either stationary or rotating rectifiers, to produce the direct current needed for the synchronous machine field

(iii) Type ST excitation systems, where excitation power is supplied through transformers or auxiliary generator windings and rectifiers

There are many different exciter models classified in one of the above three types, which are representative of commercially available exciters. PSCAD comes complete with each of these standard models.

One problem with modelling exciter systems is the inherently large time-constants involved. The user should ensure that the system is started as close to the steady state as possible (unless of course, simulation of start-up transients is required), by properly setting the machine initial conditions. It is also possible, in the case where the exciter transfer function has large time constants, to bypass these during the initial phase.

2.2.3.2 Governors

Mechanical transients usually fall in the realm of simulation using stability programs, where the details of modelling is not as comprehensive as in an electromagnetic transient program. For the duration of most transient simulation runs, the mechanical system can often be considered invariant, and users should make sure that they really need a governor model before they use it.

As mentioned above, most governor transfer functions can be simulated by using control building blocks; interfacing to the machine by either feeding the computed speed or the computed torque.
Governor models are initialized by continuously resetting internal storage locations to produce an output that is exactly equal to the mechanical torque output of the machine.

PSCAD comes complete with both hydro and thermal governor models. These models support variable time step, and have an allowance for initialization at any time through additional control inputs.

### 2.2.3.3 Stabilizers

Power system stabilizers are used to enhance the damping of power system oscillations, through excitation control. Commonly used inputs to the stabilizers are:

1. Shaft speed
2. Terminal frequency
3. Power

Most stabilizer transfer functions can be simulated through the use of control building blocks. PSCAD comes complete with both single-input and dual-input, power system stabilizers.

### 2.2.3.4 Turbines

Mechanical power supplied by turbines can often be considered invariant for the duration of most transient simulation runs. In some cases however, where provisions are made for fast-valving or discrete control in response to acceleration, prime mover effects can be significant even if the phenomena of interest span only for a few seconds. Also, to ensure the accuracy of longer simulation studies, modelling the turbine dynamics may be considered necessary.

These models support variable time step, and have an allowance for initialization at any time through additional control inputs. Most turbine dynamics can be simulated through the use of control building blocks. PSCAD comes complete with both thermal and hydraulic turbines.
2.3 Transmission Line Model in PSCAD

Overhead transmission line corridor (right-of-ways) are represented in PSCAD as two main parts: By defining the configuration of the transmission corridor itself, where the definition can include either the admittance/impedance data or the conductor and insulation properties, ground impedance data, and geometric position of all conductors within the corridor. This definition is then interfaced to the rest of the electrical system through electrical interface components (one at each end).

Three conductor transmission systems of very short length (i.e. less than 15 km for a 50 µs time step) can also be represented using an equivalent PI Section. This is accomplished through a Master Library component, called the PI Section, where only the admittance and impedance data of the line segment is entered.

A 15 km line length to a 50 µs time step is derived assuming that waves propagate through the line at the speed of light. In general however, wave propagation speed is less than the speed of light.

Using the data provided by the cross-sectional definition of the corridor, the transmission lines and cables are modelled using one of three distributed (travelling wave) models:

1. Bergeron Model
2. Frequency-Dependent (Mode) Model
3. Frequency-Dependent (Phase) Model

The most accurate of these is the Frequency Dependent (Phase) model, which represents all frequency dependent effects of a transmission line, and should be used whenever in doubt. When using the Bergeron model, impedance/admittance data can also be entered directly to define the transmission corridor.

For all of these Frequency Dependent models, detailed conductor information (i.e. line geometry, conductor radius) must be given.
2.3.1 Selecting the Proper Line Model

There are three types of distributed (i.e. travelling wave) transmission models that may be selected to represent transmission corridor: The Bergeron model, the Frequency-Dependent (Mode) Model, and the Frequency-Dependent (Phase) Model. These models exist as components in the Master Library, and each include adjustable properties. The requirements for the specific study will determine which of the three models is suitable.

(a) The Bergeron Model

The Bergeron model represents the L and C elements of a PI section in a distributed manner. It is roughly equivalent to using an infinite number of PI sections except that the resistance is lumped (i.e. ½ in the middle of the line and ¼ at each end). Like PI sections, it also accurately represents the fundamental frequency. It also represents impedances at other frequencies, except that the losses do not change. This model is suitable for studies where the fundamental frequency load-flow is most important (e.g. relay studies). This model can be:

(1) Single Conductor Model
(2) Multi- Conductor Model

When using the Bergeron model, it is not always necessary to use a tower component to represent a transmission line. In case of modelling a three-phase system the line data can be entered, in admittance or impedance format, directly by substituting the manual entry of Y,Z component.

(b) The Frequency-Dependent (Mode) Model

The Frequency-Dependent (Mode) Model represents the frequency dependence of all parameters (not just at the specified frequency as in the Bergeron model). This model uses modal techniques to solve the line constants and assumes a constant transformation. It is therefore only accurate for systems of ideally transposed conductors (or 2 conductor horizontal configurations) or single conductors.
(c) The Frequency-Dependent (Phase) Model

The Frequency-Dependent (Phase) Model also represents the frequency dependence of all parameters as in the 'Mode' model above. However, the Frequency Dependent (Phase) model circumvents the constant transformation problem by direct formulation in the phase domain. It is therefore accurate for all transmission configurations, including unbalanced line geometry.

The need for a transmission line model, which can accurately simulate the undesirable interactions between DC and AC lines in proximity to one another, has become more prevalent. Constant transformation matrix models with frequency dependent modes, such as the Frequency Dependent (Mode) model in EMTDC, have proven to be unreliable in accurately simulating such situations. In addition, inaccurate representation of unbalanced line geometry has also been a problem.

The Frequency-Dependent (Phase) model should always be the model of choice, unless another model is chosen for a specific reason. This model is the most advanced and accurate time domain line model in the world.

2.4 HVDC Model

2.4.1 Six- Pulse Converter Model Block in PSCAD

PSCAD/EMTDC provides as a single component a six-pulse valve group, as shown in Fig. 2.11 with associated Phase Locked Oscillator (PLO) firing control, sequencing drop and parallel snubber circuit.

The Fig. 2.6 component is a compact representation of a DC converter, which includes a built in 6-pulse Graetz converter bridge (can be inverter or rectifier), an internal Phase Locked Oscillator (PLO), firing and valve blocking controls and firing angle (α)/extinction angle (γ) measurements. It also includes built in RC snubber circuits for each thyristor. The general idea here is to eliminate the complex and tedious process of building a thyristor bridge, putting together controls, and coordinating the valve firing pulses involved in modeling an HVDC converter.
The 6-pulse Bridge possesses the following external inputs and outputs:

**ComBus:** Input signal to the internal Phase Locked Oscillator. This input is connected to the commutation bus though the Node Loop component.

**AO:** Input alpha order (firing angle) for the converter.

**KB:** Input block/deblock control signal

**AM:** Measured alpha (firing angle) output [radian].

**GM:** Measured gamma (extinction angle) output [radian].

The Phase Locked Oscillator (PLO) shown in Fig. 2.7 is based on the Phase Vector technique. This technique exploits trigonometric multiplication identities to form an error signal, which speeds up or slows down the PLO in order to match the phase. The output signal $\theta$ is a ramp synchronized to the Phase A commutating bus L-G voltage.

The block diagram of the PLO used in the 6-Pulse bridge component is shown in Fig. 2.7.
2.4.2 CIGRE HVDC benchmark in PSCAD

The full three-phase model of the CIGRE HVDC benchmark system is available in reference [7,10].

(A) Power Circuit Modelling

1) Converter Model:

The converters (rectifier and inverter) are modeled using *six-pulse Graetz bridge* block, shown in Fig. 2.6, which includes an internal Phase Locked Oscillator (PLO), firing and valve blocking controls, and firing angle (\( \alpha \))/extinction angle (\( \gamma \)) measurements. It also includes built-in RC snubber circuits for each thyristor. Thyristor valves are modeled as ideal devices, and therefore, negative turn-off and firing due to large (\( \frac{dv}{dt} \)) or (\( \frac{di}{dt} \)) are not considered.

2) Converter Transformer Model:

Two transformers on the rectifier side are modeled by three-phase two winding transformer, one with grounded Wye–Wye connection and the other with grounded Wye–Delta connection. The model uses saturation characteristic. The inverter side transformers use a similar model.
3) Filters and Reactive Support: Tuned filters and reactive support are provided at both the rectifier and the inverter ac sides.

(B) Control System Model

The control model mainly consists of $\alpha/\gamma$ measurements and generation of firing signals for both the rectifier and inverter. The PLO, shown in Fig. 2.7, is used to build the firing signals. The output signal of the PLO is a ramp, synchronized to the phase-A commutating bus line-to-ground voltage, which is used to generate the firing signal for Valve 1. The ramps for other valves are generated by adding 60° to the Valve 1 ramp. This process is illustrated in Fig. 2.8. As a result, an equidistant pulse is realized. The actual firing time is calculated by comparing the $\alpha$ order to the value of the ramp and using interpolation [7,10] technique. At the same time, if the valve is pulsed but its voltage is still less than the forward voltage drop, this model has a logic to delay firing until the voltage is exactly equal to the forward voltage drop. The firing pulse is maintained across each valve for 120°. The $\alpha$ and $\gamma$ measurement circuits use zero-crossing information from commutating bus voltages and valve switching times and then convert this time difference to an angle (using measured PLO frequency). Firing angle $\alpha$ (in seconds) is the time when valve $i$ turns on minus the zero crossing time for valve $i$. Extinction angle $\gamma$ (in seconds) for valve $i$ is the time at which the commutation bus voltage for valve $i$ crosses zero (negative to positive) minus the time valve $i$ turns off. The control schemes for both rectifier and inverter of the CIGRÉ HVDC system are shown in Fig. 2.9 and Fig. 2.10.

Following are the controllers used in the control schemes:

- Extinction Angle ($\gamma$ Controller),
- DC Current Controller;
- Voltage Dependent Current Order Limiter (VDCOL).
Fig. 2.8. Firing control for the PSCAD/EMTDC valve group model.

(i) Rectifier Control:

The rectifier control system uses Constant Current Control (CCC) technique. The reference for current limit is obtained from the inverter side. This is done to ensure the protection of the converter in situations when inverter side does not have sufficient dc voltage support (due to a fault) or does not have sufficient load requirement (load rejection). The reference current used in rectifier control depends on the dc voltage available at the inverter side. DC current on the rectifier side is measured using proper transducers and passed through necessary filters before they are compared to produce the error signal. The error signal is then passed through a PI controller, which produces the necessary firing angle order $\alpha$. Fig. 2.9 shows rectifier control scheme.

(ii) Inverter Control:

The Extinction Angle Control or $\gamma$ control and current control have been implemented on the inverter side. The CCC with Voltage Dependent Current Order Limiter (VDCOL) has been used here through PI controllers. The reference limit for the current control is obtained through a comparison of the external reference (selected by
the operator or load requirement) and VDCOL (implemented through lookup table) output. The measured current is then subtracted from the reference limit to produce an error signal that is sent to the PI controller to produce the required angle order. The $\gamma$ control uses another PI controller to produce gamma angle order for the inverter. The two angle orders are compared, and the minimum of the two is used to calculate the firing instant. Fig. 2.10 shows the detailed control scheme at inverter.

Fig. 2.9. CIGRE Rectifier control.
Fig. 2.10. CIGRE Inverter control scheme.
2.5 Transformer Modelling [7,10]

Transformers are represented in EMTDC through one of two fundamental methods: the classical approach and the unified magnetic equivalent circuit (UMEC) approach.

The classical approach should be used to model windings placed on the same transformer leg. That is, each phase is a separate, single-phase transformer with no interaction between phases. The UMEC method takes inter-phase interactions into account: Thus, 3-phase, 3-limb and 3-phase, 5-limb transformer configurations can be accurately modeled.

Representation of core non-linearities is fundamentally different in each model type. Core saturation in the classical model is controlled through the use of a compensating current source injection across selected winding terminals. The UMEC approach uses a fully interpolated, piecewise linear Φ-I curve to represent saturation.

Zig-zag connected transformers are modelled by these two models separately using (i) classical approach (ii) the UMEC (Unified Magnetic Equivalent Circuit) approach from three single phase, three windings, with their primary and secondary windings connected in delta and zig-zag fashion respectively as shown in Fig. 2.11a and Fig. 2.11b. This Delta - Star Zig Zag connection gives a zero degree phase shift between the primary and secondary voltages. The connections are determined based on a simple phasor based analysis.
Fig. 2.11a. Connection diagram of Delta-zig-zag transformers (Classical Model).

Fig. 2.11b. Connection diagram of Delta-zig-zag transformers (UMEC) Model.