GRID CONNECTED PHOTOVOLTAIC SYSTEM

4.1 Introduction

The conventional stand-alone systems have the advantages of simple system configuration and control scheme. However, in order to draw maximum power from PV arrays and store excess energy, battery banks are required in these systems. For high power systems, there will be an increase in system cost and weight, and narrow the application areas. Therefore, grid-connected systems, which are designed to relieve this shortcoming, have become the primary researches in PV power supply applications.

In this chapter, a general descriptive study of grid-connected PV system will be presented. This study includes: system concept, types, problems encountered, and technical interconnection standards requirements and benefits of grid connected PV system. It also includes detailed analysis of power electronic devices of grid connected PV system, DC-DC Boost converter and SVPWM inverter, its model and simulation results.

4.2 Concept of grid-connected PV system

The photovoltaic power systems have made a successful transition from a stand-alone feature to large grid-connected systems. Grid-connected PV systems can vary in size, but these systems have common components. In addition to the PV components mentioned in chapter 1, the grid connected elements necessitated to be appeared here are: the current controller and output inverter filter, as well as a metering equipment to monitor the power that is fed into the grid and vice versa.

Grid connected PV systems have become one of the important applications of solar energy. The simple configuration of such a system and its low cost has attracted broad interest. The wide acceptance and utilization of PV power generation, albeit in any form, are still dependent upon lowering the capital cost of system installation. Moreover, for grid-connected PV plants, it makes good economic sense to maximize the amount of power generated by PV arrays and thus transferred to the grid at all times. This will lead to the scaling down of PV arrays and converters, thus, resulting in a lower cost system. The utility grid acts as storage means for the PV arrays, as shown in Fig.4.1 which will be proposed as a case study in this project.
Interconnection of power generation from PV energy sources to the grid needs static DC-DC and DC-AC converters. Connection of the converters with the distribution network is done using passive filters in order to attenuate the voltage and current harmonics.

**Output filter**

Because of rapid changes in voltages and currents within a switching converter, power electronic equipment is a source of Electromagnetic Interference (EMI). Therefore, it is necessary to insert an inverter output filter which must be characterized by its capability to eliminate the maximum harmonics (voltage & current) exit from the inverter. Fig. 4.2 illustrates types of the output filters.

**4.3 Types of grid-connected PV systems**

Two types of grid-connected PV systems are generally found: Embedded and Distributed generations.

The embedded PV generation, from hundreds of kW to a MW, tied to the utility distribution network can be a cost-effective solution to the problems of overload or power quality at critical points in the network. It would be more cost effective to install a PV plant feeding power to a substation at the critical point rather than implementing expensive upgrades. With increasing demands of power in developing countries, embedded generation
would be an attractive alternative solution for them. Currently, there are not many studies developed for distribution network of a utility in a developing country. Studies should be carried out as soon as possible to unlock a potentially large market. The PV system could provide an increased reliability in terms of supply, and could bring benefits to the economy to countries that introduces.

The distributed generation is designated to supply consumers where the power demand is less than a few kWs (<10kW). Individual PV systems on buildings (residential or commercial) connected to the grid constitute the distributed generation. The purpose of distributed generation is to avoid buying electricity from the utility as possible. The great advantage of distributed generation from buildings is that very large area can be covered without employing additional land area.

### 4.4 Problems and risks involving grid-connected PV systems

The problems that should be anticipated involving interconnection of PV system to the grid would include:

- Disconnection of PV system if the grid fails (islanding problems)
- Earthing and lightning protection
- Quality of power input to the grid
- Effects of multiple systems on a part of the grid, particularly unbalanced single phase generation
- Reliable metering of the power flows
- Technical and financial risks.

Here are some details concerning these problems:

**Islanding problems**

The phenomenon of islanding is the operating of the PV system in the absence (poor grid reliability) of the grid. This phenomenon could cause transient over-currents when the grid power is connected back. Protection control circuits are developed and constantly revised to protect the grid and the PV from this problem and other problems such as lightning surges, short circuits and grounding.
Quality of power input to the grid

Many norms impose several rules to insure a high quality of power injected to the grid. For example, it states that these PV systems should be compatible with the voltage, wave shape and frequency of the grid. When either the power source/generators or the loads have solid-state equipments, harmonic currents will flow in the system. These harmonics can cause detrimental destruction to the control devices. Overrating of generators, transformers, cable, motors and circuit breakers are needed when higher harmonics are significant. Special voltage generator voltage control systems are required to avoid erratic operations.

Technical and financial risks

The electricity utilities present its reluctance to this technology with risks that they have no historical basis for quantifying. Some of the risks that were highlighted are:

- Technical risks: there is a possibility that the system will not be performed as specified;
- Construction risks: the possibility of going over budget, or construction of the system cannot be completed by the due date;
- Operating risks: the possibility that the system breaks down or power is unavailable when it is in demand. Other operating risks would include islanding
- Financial limitations: high costs of finance based on the perceived risks above.

4.5 Benefits of grid connected PV system

In this section, the benefits of connecting a PV system to the grid will be discussed. Some of the advantages of grid-connected PV system over stand-alone systems would include the savings from wiring costs, batteries and the possibility that grid-connected PV system could sell off the surplus electricity to the utility. Some of the benefits of grid-connected PV systems are briefly discussed in the following sections:

Reduction in labor costs

By following the requirements set by IEEE, UL & the NEC®, the utility would remove the need to come out with requirements or standards of its own. The use of two-way metering also would reduce the need for separate processing of meter readings for electricity that is delivered to and from the customers.
Distributed generation benefits

Studies have shown that there is a direct, measurable economic benefit of distributed generation, which includes reduced energy losses in transmission and distribution lines. Other advantages would include voltage support, reactive power losses, deferred substation upgrades, deferred transmission capacity and reduced demand for spinning reserve capacity.

Environmental benefits

PV electricity generation would reduce the effects of pollution caused by conventional power generators. Looking at the greenhouse effects, PV electricity generation would provide a better alternative to the pollution problems. Grid connected PV systems reduce the consumption of natural resources, such as coal, oil, etc, therefore diminishing the need for new power stations.

Reduction in equipment costs

Inverters that follows the UL-1741 standards would provide safety and power quality protection, therefore eliminates the need for the utility to implement a separate protection devices on its network.

4.6 The Proposed system

The schematic block diagram of a grid connected photovoltaic system proposed in this thesis is shown in fig.4.3. For maximum utilization efficiency of a PV array it is necessary to operate the PV array at maximum power point. But it is difficult to operate the cell at MPP always as it depends on the atmospheric conditions such as cell temperature ($T_c$) and solar irradiance ($G$). In this thesis a neural network based MPPT is proposed.

A three-phase six switch inverter and a dc-dc boost converter interfaces the PV array with an a.c grid. The interface is very important as it affects the operation of the PV cell system as well as the power grid. A neural network based high performance current regulator is used to control the boost converter to track the maximum power continuously, and space vector modulation PWM scheme in combination with neural network has been used to control the inverter. In the next preceding sections the modeling of boost converter and three phase inverter are analyzed and the simulation results for these devices are
presented when they are interfaced with PV array to track the maximum power continuously by using the neural network based MPP tracking algorithm.

4.7 DC-DC Boost Converter

In this section Introduction to state space average analysis is given, modeling of DC-DC boost converter is analyzed using state-space averaging technique and finally simulation results of boost converter is presented when it is interfaced with the PV array to extract maximum power continuously.

4.7.1 State-space averaging technique

To study the behavior of linear time invariant control systems, we approach the time-domain methods or frequency domain methods. Such an approach for the study is called conventional approach of study. In all these approaches, we model the given system in the form of a transfer function. The limitations associated with this transfer function approach are:

- Significant initial conditions in obtaining precise solution of any system, loose their importance.
- These methods are insufficient and troublesome to give complete time domain solution of higher order systems.
- They are not very much convenient for the analysis of multiple input multiple output systems.
- These methods are applicable only to linear time invariant systems.
• They give analysis of systems for specific types of inputs like step, ramp etc.
To analyze the systems it is absolutely necessary to overcome the above difficulties. The modern method discuss in this thesis uses the concept of the system considering all initial conditions. This technique is called State Space Analysis. This is essentially a time-domain approach.

**Advantages of State Space Approach**

- The method takes into account the effect of all initial conditions.
- It can be applied to nonlinear as well as time varying systems.
- The system can be designed for the optimal conditions precisely by using this method.
- As the method involves matrix algebra, can be conveniently adopted for the digital computers.
- The matrix notation greatly simplifies the mathematical representation of the system.

**Concept of State**

Consider a cricket match. The score in the cricket match must be updated at every instant from the knowledge and information of the total score before that instant. This procedure of updating the score continues till the end of the match when we get exact and precise score of the entire match. This updating procedure has main importance in understanding the concept of the state.

Consider the network shown in the figure (4.4). To find out $V_{\text{out}}$ the knowledge of the initial capacitor voltage must be known. Only information about $V_{\text{in}}$ will not be sufficient to obtain precisely the $V_{\text{out}}$ at any time $t \geq 0$. Such systems in which the output is not only dependent on the input but also on the initial conditions are called systems with memory or dynamic systems.

While if in the above network capacitor 'C' is replaced by another resistance $R_L$, then output will be dependent only on the input applied $V_{\text{in}}$. Such systems in which the
output is dependent only on the input applied at $t=0$ are called systems with zero memory or static systems.

The state of the system at any time $t$ is actually the combined effect of the values of all the different elements of the system which are associated with the initial conditions of the system. Thus, the complete state of the system can be considered to be a vector having components which are the variables of system which are closely associated with initial conditions. So state can be defined as vector $X(t)$ called state vector.

Terminology:

**State**: The state of a dynamic system is defined as a minimum; set of variables such that the knowledge of these variables at $t=t_0$ together with the knowledge of the inputs for $t \geq t_0$, completely determines the behavior of the system for $t > t_0$.

**State Variables**: The variables involved in determining the state of a dynamic system $X(t)$, are called state variables. $X_1(t), X_2(t), \ldots, X_n(t)$ are nothing but the state variables. These are normally energy storing elements contained in the system.

**State Vector**: The ‘$n$’ state variables necessary to describe the complete behavior of the system can be considered as ‘$n$’ components of a vector $X(t)$ called the state vector at time ‘$t$’. The state vector $X(t)$ is the vector sum of all the state variables.

**State Space**: The space whose coordinate’s axes are nothing but the ‘$n$’ state variables with time as the implicit variable is called state space. The state space model of linear time invariant system is given by:

**State Equation**: \[
\dot{X}(t) = AX(t) + BU(t)
\]

**Output Equation**: \[
Y(t) = CX(t)
\]

Where \[X(t) = \text{State Vector}, U(t) = \text{Input Vector}, Y(t) = \text{Output Vector},\]

$A$ = $n \times n$ matrix called Evolution Matrix

$B$ = $n \times m$ matrix called Control Matrix

$C$ = $p \times n$ matrix called Observation Matrix
4.7.2 Modeling of DC-DC Boost converter

Since, solar cells have relatively low conversion efficiency and the improvement of overall system efficiency is an important factor. This can be partly achieved by using high efficiency intermediate boost converter with maximum power point controller. The steady-state voltage and current relations for this converter operating in continuous current mode are derived using state-space averaging technique. The basic equivalent circuit for the boost converter shown is below:

![Circuit Diagram of DC/DC boost converter]

Fig. 4.6: Circuit Diagram of DC/DC boost converter

This converter works under two different modes, when the switch is ON-Mode(Mode-I), and when the switch is in OFF-Mode(Mode-II). The state space modeling is applied to boost converter for two modes. Then we will find the average state space model of the boost converter for the Boost converter.

![Circuit Diagram of DC/DC boost converter during Mode-I](a) ![Circuit Diagram of DC/DC boost converter during Mode-II](b)

Fig. 4.7a: Circuit Diagram of DC/DC boost converter during Mode-I

Fig. 4.7b: Circuit Diagram of DC/DC boost converter during Mode-II
When the switch S is On and diode D is Off, the state space representation of the main circuit during mode-I from fig(4.7a) can be written as:

\[ \dot{X}_1 = A_1 X_1 + B_1 V_{dc} \]

\[ V_{o1} = C_1^T X \]  

(4.1)

Where \( X_1 = \begin{bmatrix} \frac{1}{L} \\ \frac{V_c}{L} \end{bmatrix} \), \( A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \), \( B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \), \( C_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \),

And \( \dot{X} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} \) \( (4.2) \)

When the switch S is Off and diode D is On, the state space representation of the main circuit during mode-II from fig(4.7b) can be written as:

\[ X_2 = A_2 X_2 + B_2 V_{dc} \]

\[ V_{o2} = C_2^T X \]  

(4.3)

Where \( A_2 = \begin{bmatrix} 0 & \frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \), \( B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \), \( C_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \) \( (4.4) \)

Therefore, the average state-space model of the main circuit at the operating point D is:

\[ \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} \text{ at D} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} * D + \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} * (1-D) \]  

(4.5)

\[ \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \begin{bmatrix} V_o \end{bmatrix} \]  

(4.6)

\[ V_o \text{ at D} = V_{o1} * D + V_{o2} * (1-D) \]  

(4.7)
\[ V_o = [0 \ 1][\frac{e_L}{V_c}] \quad (4.8) \]

Where equations (3.7) and (3.8) represents state equation and the output equation.

### 4.7.3 Controller Design for Boost Converter

Since, Solar cells have relatively low conversion efficiency and the improvement of overall system efficiency is an important factor in the area of PV systems. This can be partly achieved by using high efficiency intermediate converters. A boost converter coupled with PV array is presented in this section.

The output current \( I_{pv} \) and the terminal voltage \( V_{pv} \) are measured at a instant and compared with \( I_{mp} \) of the neural network where \( I_{mp} \) is optimal operating point which yields maximum power from PV module. This error is processed through the PI-controller which generates a control signal to shift the operating point \( I_{pv} \) and \( V_{pv} \) to the optimal operating point. The main components of the boost converter can be determined by the prescribed technical specifications, such as the rated and peak voltage and current, input current ripple, and output voltage ripple, etc., using the classic boost dc/dc converter design procedure. The component values for the dc/dc converter used in this paper are listed in Table I. Based on the converter model in fig.(4.8), a PI current controller \((kdp + kdi/s)\) is designed by trial and error method.
### TABLE 4.1
PARAMETERS OF THE BOOST dc/dc CONVERTER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Ripple($\Delta I_L$)</td>
<td>0.266 A</td>
</tr>
<tr>
<td>Voltage Ripple($\Delta V_c$)</td>
<td>0.17777 V</td>
</tr>
<tr>
<td>Inductance ($L$)</td>
<td>2 mH</td>
</tr>
<tr>
<td>Capacitance ($C$)</td>
<td>150 µF</td>
</tr>
</tbody>
</table>

### 4.8 Three Phase Inverter

A three-phase six-switch PWM VSI is used to convert the power available at the dc bus to ac power. Fig 4.9 shows the main circuit of the three-phase voltage source inverter connected to the utility grid through the $LC$ filter ($L_f$ and $C_f$) and the coupling inductor ($L_s$). $R_f$ and $R_s$ in the figure are the parasitic resistances of the filter inductor and the coupling inductor, respectively.

In this section, Using the classic electrical circuit theory and state-space averaging technique, a detailed state-space description of the inverter can be obtained. An Introduction about space vector PWM is explained.

![Fig 4.9: Three Phase DC/AC Voltage Source Inverter](image-url)
4.8.1 State-Space Model of Three Phase Inverter

For deducing convenience, the neutral point N of the AC system is chosen as the common potential reference point. For the purpose of simplicity, only the inverter under balanced loads and without a neutral line is discussed. Define the following switching functions:

\[ d_1^* = \begin{cases} +1 & S_a^+ \text{ ON} \\ -1 & S_a^- \text{ ON} \end{cases} \]

\[ d_2^* = \begin{cases} +1 & S_b^+ \text{ ON} \\ -1 & S_b^- \text{ ON} \end{cases} \]

\[ d_3^* = \begin{cases} +1 & S_c^+ \text{ ON} \\ -1 & S_c^- \text{ ON} \end{cases} \]

(4.9)

\[ V_{an}, V_{bn}, \text{ and } V_{cn} \text{ (the inverter output voltages between each phase and its imaginary neutral point n)} \text{ can be expressed as:} \]

\[ \begin{cases} V_{an} = \frac{d_1^*}{2} V_{dc} \\ V_{bn} = \frac{d_2^*}{2} V_{dc} \\ V_{cn} = \frac{d_3^*}{2} V_{dc} \end{cases} \]

(4.10)

where \( V_{dc} \) is the DC bus voltage.

The output phase potentials of the inverter, \( V_a, V_b \) and \( V_c \) can be obtained as:

\[ \begin{cases} V_a = V_{an} + V_n \\ V_b = V_{bn} + V_n \\ V_c = V_{cn} + V_n \end{cases} \]

(4.11)

where \( V_n \) is the voltage between the point n and the common reference neutral point N.

Since \( i_{fa} + i_{fb} + i_{fc} = 0 \) and \( e_a + e_b + e_c = 0 \), \( v_n \) is obtained as

\[ v_n = -\frac{v_{dc}}{6} \sum_{k=1}^{3} d_k^* \]

(4.12)
For the circuit shown in Figure, the following dynamic equations can be obtained:

\[
\begin{align*}
V_a &= L_f \frac{di_f}{dt} + R_f i_f + V_{sa} \\
V_b &= L_f \frac{di_f}{dt} + R_f i_f + V_{sb} \\
V_c &= L_f \frac{di_f}{dt} + R_f i_f + V_{sc}
\end{align*}
\]  
(4.13)

\[
\begin{align*}
i_{f_a} &= i_{2a} + C_f \frac{d(v_{2a} - v_{2b})}{dt} + C_f \frac{d(v_{2a} - v_{2c})}{dt} \\
i_{f_b} &= i_{2b} + C_f \frac{d(v_{2b} - v_{2a})}{dt} + C_f \frac{d(v_{2b} - v_{2c})}{dt} \\
i_{f_c} &= i_{2c} + C_f \frac{d(v_{2c} - v_{2a})}{dt} + C_f \frac{d(v_{2c} - v_{2b})}{dt}
\end{align*}
\]  
(4.14)

\[
\begin{align*}
R_s i_{sa} + L_s \frac{di_{sa}}{dt} &= V_{sa} - e_A \\
R_s i_{sb} + L_s \frac{di_{sb}}{dt} &= V_{sb} - e_B \\
R_s i_{sc} + L_s \frac{di_{sc}}{dt} &= V_{sc} - e_C
\end{align*}
\]  
(4.15)

Writing the above equations into the state-space form:

\[
\dot{X}_{abc} = A_{abc} X_{abc} + B_{abc} U_{abc}
\]

(4.16)

Where \( X_{abc} = [i_{f_a}, i_{f_b}, i_{f_c}, v_{sa}, v_{sb}, v_{sc}, i_{sa}, i_{sb}, i_{sc}]^T \)

\[
U_{abc} = [V_{dc}, e_A, e_B, e_C]^T
\]
\[ A_{\alpha \beta \gamma} = \begin{bmatrix}
\frac{-R_f}{L_f} & 0 & 0 & -\frac{1}{L_f} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{-R_f}{L_f} & 0 & 0 & -\frac{1}{L_f} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{-R_f}{L_f} & 0 & 0 & -\frac{1}{L_f} & 0 & 0 & 0 \\
\frac{1}{3C_f} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{3C_f} & 0 & 0 \\
0 & \frac{1}{3C_f} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{3C_f} & 0 \\
0 & 0 & \frac{1}{3C_f} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{3C_f} \\
0 & 0 & 0 & \frac{1}{L_s} & 0 & 0 & -\frac{R_s}{L_s} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{L_s} & 0 & 0 & -\frac{R_s}{L_s} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{L_s} & 0 & 0 & -\frac{R_s}{L_s}
\end{bmatrix} \]
4.8.2 dq Representation of the State-Space Model

The dq transformation transfers a stationary 3-coordinate (abc) system to a rotating 2-coordinate (dq) system. The dq signals can be used to achieve zero tracking error control. Due to this merit, the dq transformation has been widely used in PWM converter and rotating machine control. Using the dq transformation (see Appendix A), the system state-space equation given in can be represented in the rotating dq frame as:

$$\dot{X}_{dq} = A_{dq} X_{dq} + B_{dq} U_{dq}$$  \hspace{1cm} (4.17)

Where,

$$X_{dq} = [i_{dq} \quad v_{dq}]^T$$

$$U_{dq} = [v_{dc} \quad e_d \quad e_q]^T$$

$$[i_{dq}] = T_{abc/dq} \begin{bmatrix} [i_{fa}] \\ [i_{fb}] \\ [i_{fc}] \end{bmatrix} , \ [v_{dq}] = T_{abc/dq} \begin{bmatrix} [v_{fa}] \\ [v_{fb}] \\ [v_{fc}] \end{bmatrix}$$

and $$[e_d] = T_{abc/dq} \begin{bmatrix} [e_a] \\ [e_b] \end{bmatrix}$$

and

$$B_{abc} = \begin{bmatrix} \frac{L_f}{2} & 0 & 0 \\ \frac{L_f}{2} & 0 & 0 \\ \frac{L_f}{2} & 0 & 0 \\ 0 & \frac{1}{L_s} & 0 \\ 0 & 0 & \frac{1}{L_s} \\ 0 & 0 & 0 \end{bmatrix}$$
\[
A_{dq} = \begin{bmatrix}
-R_f & \omega & -\frac{1}{L_f} & 0 & 0 & 0 \\
-\omega & R_f & 0 & -\frac{1}{L_f} & 0 & 0 \\
\frac{1}{2c_f} & 0 & 0 & -\frac{1}{2c_f} & 0 & 0 \\
0 & \frac{1}{3c_f} & -\omega & 0 & 0 & -\frac{1}{3c_f} \\
0 & 0 & \frac{1}{L_s} & 0 & -\frac{R_s}{L_s} & \omega \\
0 & 0 & 0 & \frac{1}{L_s} & -\omega & -\frac{R_s}{L_s}
\end{bmatrix}
\]

and

\[
B_{dq} = \begin{bmatrix}
\frac{f_1(t, d_1, d_2, d_3)}{L_f} & 0 & 0 \\
\frac{f_2(t, d_1, d_2, d_3)}{L_f} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -\frac{1}{L_f}
\end{bmatrix}
\]

\(f_1\) and \(f_2\) are obtained as:

\[
f_1(t, d_1, d_2, d_3) = \frac{1}{3} \left[ \sin(\omega t) \left( d_1 - \frac{1}{3} \sum_{k=1}^{3} d_k \right) + \sin \left( \omega t - \frac{2\pi}{3} \right) \left( d_2 - \frac{1}{3} \sum_{k=1}^{3} d_k \right) \\
+ \sin \left( \omega t - \frac{4\pi}{3} \right) \left( d_3 - \frac{1}{3} \sum_{k=1}^{3} d_k \right) \right]
\]

\[
f_2(t, d_1, d_2, d_3) = \frac{1}{3} \left[ \cos(\omega t) \left( d_1 - \frac{1}{3} \sum_{k=1}^{3} d_k \right) + \cos \left( \omega t - \frac{2\pi}{3} \right) \left( d_2 - \frac{1}{3} \sum_{k=1}^{3} d_k \right) \\
+ \cos \left( \omega t - \frac{4\pi}{3} \right) \left( d_3 - \frac{1}{3} \sum_{k=1}^{3} d_k \right) \right]
\]

4.8.3 Controller Design for Three Phase Inverter
To meet the requirements for interconnecting a PV cell system to a utility grid and control power flow between them, it is necessary to shape and control the inverter output voltage in amplitude, angle, and frequency. In this section, a space vector PWM controller is designed for the inverter to track maximum power. The component values for the three phase inverter used in this thesis are listed as filter inductance and capacitance are $L_f = 800\,\mu\text{H}$ and $C_f = 400\,\mu\text{F}$, coupling inductance=$2\,\text{mH}$. The parasitic resistances of the filter inductor and the coupling inductor $R_f$ and $R_S$ are each $5\,\Omega$.

The $dq$ transformation transfers a stationary ($abc$) system to a rotating ($dq0$) system. The transformation decreases the number of control variables from 3 to 2 (component 0 will be zero) if the system is balanced. Moreover, the $dq$ signals can be used to achieve zero tracking error control. Due to these merits, $dq$ transformation has been widely used in PWM converter/inverter control and is also applied for the inverter control in this paper as shown in fig. (4.10). For accurate current regulation, all AC three phase variables are represented in their d-q vector forms using a reference frame synchronously rotating with the supply voltage. Two PI regulators one for d component the other q component of the current vector are required. The advantage of employing a synchronously rotating reference frame (SRRF) current regulator is well known. The input and the output are DC rather than sinusoidal quantities, hence, enabling the controller to obtain a complete elimination of phase error between the reference and controlled currents at any operating point. The q component of the command current vector is set to zero, while d is defined to be equal to maximum current output of the neural network.
4.8.4 Space Vector PWM

**Definition of Space-Vector**

The space vector $V_s$ constituted by the pole voltage $V_{ao}$, $V_{bo}$, $V_{co}$ is defined as:

$$V_{bo} \exp(\text{ }) + V_{co} \exp(\text{ })$$  \hspace{1cm} (4.18)

The relationship between the phase voltages $V_{an}$, $V_{bn}$, and $V_{cn}$ and the pole voltages $V_{ao}$, $V_{bo}$, and $V_{co}$ is given by:

$$V_{ao} = V_{an} + V_{no}; \quad V_{bo} = V_{bn} + V_{n}$$  \hspace{1cm} (4.19)

Since, $V_{an} + V_{bn} + V_{cn} = 0$; then

$$V_{no}$$  \hspace{1cm} (4.20)

where, $V_{no}$ is the common mode voltage as mentioned before.

From eqn.3.18 and eqn.3.19 it is evident that the phase voltages $V_{an}$, $V_{bn}$, $V_{cn}$ also result in the same space vector $V_s$.

The space vector $V_s$ can also be resolved into two rectangular components namely $V_a$ and $V_b$.

It is customary to place the $\alpha$-axis along the A-phase axis of the induction motor. Hence:

$$V_{\alpha} = V_{\alpha n} + V_{\alpha o}; \quad V_{\beta} = V_{\beta n} + V_{\beta}$$  \hspace{1cm} (4.21)

**Principle of Space Vector Modulation**

An inverter is nowadays commonly used in variable speed AC motor drives to produce a variable, three phases and AC output voltage from a DC voltage. Since AC
voltage is defined by two characteristics, amplitude and frequency, it is essential to work out a strategy that permits control over both these quantities.

Pulse Width modulation (PWM) controls the average output voltage a sufficiently small period, called switching period, by producing pulses of variable duty-cycles. Here, sufficiently small means that the switching period is small compared to the desired output voltage so that the output voltage may be consider as equal to desired.

**Fig.4.11:** Three-phase voltage source PWM inverter

The circuit model of a typical three-phase voltage source PWM inverter is shown in Fig.4.11. S\(_1\) to S\(_6\) are the six power switches that shape the output, which are controlled by the switching variables a, a\(^I\), b, b\(^I\), c and c\(^I\). When an upper transistor is switched on i.e., when a, b or c is 1, the corresponding lower transistor is switched off i.e., the corresponding a\(^I\), b\(^I\) or c\(^I\) is 0. Therefore, the on and off states of the upper transistors S\(_1\), S\(_3\)and S\(_5\) can be used to determine the output voltage.

The relationship between the switching variable vector \([a \ b \ c]^T\) and the phase voltage vector \([V_a \ V_b \ V_c]^T\) is given by eq.3.22 in the following:

\[
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} = \frac{V}{2}
\]  

(4.22)

Also, the relationship between the switching variable vector \([a \ b \ c]^T\) and line-line voltage vector \([V_{ab} \ V_{bc} \ V_{ca}]^T\) can be expressed below in eq.3.23.
As illustrated in Fig.4.12, there are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. According to eq. 3.22 & 3.23, the eight switching vectors, output line to neutral voltage, and output line-line voltages in terms of DC-link $V_{dc}$, are given in Table 4.1 and Fig.4.12 shows the eight inverter voltage vectors ($\vec{V}_0$ to $\vec{V}_7$).

![Diagram of inverter voltage vectors](image)

**Table 4.2 switching vectors, line to neutral voltages and line to line voltages**

<table>
<thead>
<tr>
<th>Voltage Vector</th>
<th>Switching Vectors</th>
<th>Line to neutral voltage</th>
<th>Line to line voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0$</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>
### abc-Frame to dq-Frame Transformation

To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig.4.13.

![Fig.4.13: The relationship of abc reference frame and stationary dq reference frame](image)

From Fig 4.13, the relation between these two reference frames is given below

\[ \mathbf{f}_{dqo} = K_s \mathbf{f}_{abc} \]

where

\[
K_s = \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
1/2 & 1/2 & 1/2
\end{bmatrix}
\]

\[ \mathbf{f}_{dqo} = [f_d \ f_q \ f_o]^T, \quad \mathbf{f}_{abc} = [f_a \ f_b \ f_c]^T, \] and \( f \) denotes either a voltage or a current variable.
As described in Fig.4.13, this transformation is equivalent to an orthogonal projection of \([a \ b \ c]^t\) on to the two-dimensional perpendicular to the vector \([1 \ 1 \ 1]^t\) (the equivalent \(\alpha-\beta\) plane) in a three-dimensional coordinate system.

The approach of pulse width modulation that is described in this application is based on the space vector representation of the voltage in the stationary reference frame. It is known that a balanced three phase set of voltages is represented in the stationary reference frame by a space vector of constant magnitude, equal to the amplitude of the voltages, and rotating with angular speed \(\omega = 2\pi f\text{ref.}\)

\[
\bar{V} = V_\alpha + jV_\beta = \frac{2}{3} \left( V_{\alpha 0} + V_{b 0} \exp\left(j\frac{2\pi}{3}\right) + V_{c 0} \exp\left(-j\frac{2\pi}{3}\right) \right) \tag{4.24}
\]

As will be seen in the next section, the eight possible states of an inverter are represented as two null-vectors and six active-state vectors forming a hexagon. SVM now approximates the rotating reference vector in each switching cycle by switching between the two nearest active-state vectors and the null-state vectors. In order to maintain the effective switching frequency of the power devices at a minimum, the sequence of toggling between these vectors is organized such that only one leg is affected in every step. It may be anticipated that the maximum obtainable output voltage is increased with ordinary SVM up to 90.6% of the inverter capability. It is also a relatively easy task in order to reach full inverter capability.

**Generation of the PWM switching signals**

With a three-phase voltage source inverter there are eight possible states. For instance, in the fig.4.44 the upper switch of the inverter pole A is on, where as the other legs both have the lower switch turned on.
Fig.4.14: Three phase PWM inverter

Hence the pole voltages are \( \left( \frac{1}{2}V_{dc}, \frac{1}{2}V_{dc}, \frac{1}{2}V_{dc} \right) \) for poles A, B, C respectively. In the following this state is denoted as (1, 0, 0) and, according to the Eq.3.24, may be depicted as space vector

\[
\mathbf{V}_1 = \frac{2}{3}V_{dc}e^{j\theta}
\]  

(4.25)

Repeating these considerations for the other states one finds two null-vectors \( \mathbf{V}_0 \) for state (0,0,0) and \( \mathbf{V}_7 \) for state (1,1,1) and six active-vectors \( \mathbf{V}_1 \) to \( \mathbf{V}_6 \) shown in Fig.4.45. The six active-states, are represented by space vectors

\[
\mathbf{V}_k = \frac{2}{3}V_{dc}e^{j(k-1)\frac{2\pi}{6}}
\]  

with \( k = 1 \ldots 6 \)  

(4.26)

Shapes the axes of a regular hexagon and dividing it into six equal sectors denoted as 1, 2, 3, 4, 5 and 6 as shown in Fig.4.15. The six non-zero vectors(\( \mathbf{V}_1 \) to \( \mathbf{V}_6 \)) feed electric power to the load.

Fig.4.15: Switching vector and Sectors
The angle between any adjacent two non-zero vectors is $60^\circ$. A mean space vector $\bar{V}_{\text{ref}}$ over switching period $T_S$ can be defined. Assuming $T_S$ is sufficiently small $\bar{V}_{\text{ref}}$ can be considered approximately constant during this interval, and it is this vector, which generates the fundamental behavior of the machine.

The continuous space Vector Modulation technique is based on that every vector $\bar{V}_{\text{ref}}$ inside the hexagon can be expressed as a weighted average combination of the two adjacent active space vectors and null-state vectors 0 and 7. Therefore, in each cycle imposing the desired reference vector may be achieved by switching between these four inverter states. Looking at Fig. 4.15 one finds that, assuming $\bar{V}_{\text{ref}}$ to be laying in sector $k$, the adjacent active vectors are $\bar{V}_k$ and $\bar{V}_{k+1}$, where $k+1$ is set to 1 assuming $\bar{V}_{\text{ref}}$ to be laying in sector to be laying in sector $k$, the adjacent active vectors are $\bar{V}_k$ and $\bar{V}_{k+1}$, where $k+1$ is set to 1 for $k=6$.

In order to obtain optimum harmonic performance and the minimum switching frequency for each of the power devices, the state sequence is arranged such that switching only one inverter leg performs the transition from one state to the next. This condition is met if the sequence begins with one zero-state and the inverter poles are toggled until the other null-state is reached. To complete the cycle the sequence is reversed, ending with the first zero-state. If, for instance, the reference vector sits in sector 1, the state sequence has to be...0127210… Whereas in sector 4 it is ...0547450…. The central part of the Space Vector Modulation strategy is the computation of both the active and zero-state times for each modulation cycle. These may be calculated by equating the applied average voltage to the desired value.

In the following, $T_K$ denotes half the on–time of vector $\bar{V}_k$. $T_0$ is the half the null-state time. Hence, the on-times are evaluated by the following equations:

\[ \int_0^{T_K} P_{\text{off}} \, dt = \int_0^{T_0} P_0 \, dt + \int_0^{T_K} P_0 \, dt + \int_0^{T_K} P_{k+1} \, dt + \int_0^{T_K} P_{k+2} \, dt \]

\[ \frac{T_K}{2} = T_0 + T_K + T_{K+1} \]
Taking into account that $\tilde{V}_0 = \tilde{V}_7 = 0$ and that $\tilde{V}_{ref}$ is assumed constant and the fact that $\tilde{V}_K$ and $\tilde{V}_{K+1}$ are constant vectors, now the eq.3.11 reduces to

$$\tilde{V}_{ref} \frac{T_s}{2} = \tilde{V}_K T_k + \tilde{V}_{K+1} T_{k+1} (4.29)$$

Splitting this vectorial equation into its real and imaginary components, from equation 4.52 follows that:

$$\begin{pmatrix} V_a \\ V_b \end{pmatrix} \frac{T_s}{2} = \frac{2}{3} V_{dc} \begin{bmatrix} \cos \left( \frac{(k-1)\pi}{3} \right) & \cos \frac{k\pi}{3} \\ \sin \left( \frac{(k-1)\pi}{3} \right) & \sin \frac{k\pi}{3} \end{bmatrix} \begin{pmatrix} T_k \\ T_{k+1} \end{pmatrix} (4.30)$$

$$= \frac{2}{3} V_{dc} \begin{bmatrix} \cos \left( \frac{(k-1)\pi}{3} \right) & \cos \frac{k\pi}{3} \\ \sin \left( \frac{(k-1)\pi}{3} \right) & \sin \frac{k\pi}{3} \end{bmatrix} \begin{pmatrix} T_k \\ T_{k+1} \end{pmatrix}$$

(4.31)

where $k$ is to be determined from the argument of the reference vector:

$$\alpha = \arg \begin{pmatrix} V_a \\ V_b \end{pmatrix} (4.32)$$

such that

$$\frac{(k-1)\pi}{3} < \arg \begin{pmatrix} V_a \\ V_b \end{pmatrix} < \frac{k\pi}{3} (4.33)$$

The request of minimal number of computations per cycle is met if in every odd sector the sequence of applied vectors is $\tilde{V}_0, \tilde{V}_k, \tilde{V}_{k+1}, \tilde{V}_7, \tilde{V}_{k+1}, \tilde{V}_k, \tilde{V}_0$, whereas in even sector the active-vectors are applied in the reversed order, hence, $\tilde{V}_0, \tilde{V}_{k+1}, \tilde{V}_k, \tilde{V}_7, \tilde{V}_k, \tilde{V}_{k+1}, \tilde{V}_0$.

Solving eq 3.31 one finds:
\[
\begin{bmatrix}
T_k \\
T_{k+1}
\end{bmatrix} = \frac{\sqrt{3}}{2} \frac{T_s}{V_{dc}} \begin{bmatrix}
\sin \left( \frac{k\pi}{3} - \frac{(k-1)\pi}{3} \right) & -\cos \left( \frac{k\pi}{3} - \frac{(k-1)\pi}{3} \right) \\
-\sin \left( \frac{(k-1)\pi}{3} \right) & \cos \left( \frac{(k-1)\pi}{3} \right)
\end{bmatrix} \begin{bmatrix}
V_a \\
V_\beta
\end{bmatrix}
\]

(4.34)

The total null-state time \( T_0 \) may be divided in an arbitrary fashion between the two zero-states. A common solution is to divide \( T_0 \) equally between the two null-state vectors \( \vec{V}_0 \) and \( \vec{V}_7 \). From eq. 3.28, \( T_0 \) results as:

\[
T_0 = \frac{T_s}{2} - (T_k + T_{k+1})
\]

(4.35)

As an example for the switching scheme, in sector 1 one finds:

Fig.4.16: PWM output signals for a particular case with a reference vector sitting in sector 1

Fig.4.17: switching schemes for the six sectors
Table 4.3 Switching sequences for two-level inverter in all the sectors for SVM
### Table 4.4 Switching time calculation at each sector

<table>
<thead>
<tr>
<th>Sector</th>
<th>Upper switches (S1, S2, S3)</th>
<th>Lower switches (S4, S5, S6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( S1 = T1 + T2 + T0/2 ) &lt;br&gt; ( S3 = T2 + T0/2 ) &lt;br&gt; ( S5 = T0/2 )</td>
<td>( S4 = T0/2 ) &lt;br&gt; ( S6 = T1 + T0/2 ) &lt;br&gt; ( S2 = T1 + T2 + T0/2 )</td>
</tr>
<tr>
<td>2</td>
<td>( S1 = T1 + T0/2 ) &lt;br&gt; ( S3 = T1 + T2 + T0/2 ) &lt;br&gt; ( S5 = T0/2 )</td>
<td>( S4 = T2 + T0/2 ) &lt;br&gt; ( S6 = T0/2 ) &lt;br&gt; ( S2 = T1 + T2 + T0/2 )</td>
</tr>
<tr>
<td>3</td>
<td>( S1 = T0/2 ) &lt;br&gt; ( S3 = T1 + T2 + T0/2 ) &lt;br&gt; ( S5 = T2 + T0/2 )</td>
<td>( S4 = T1 + T2 + T0/2 ) &lt;br&gt; ( S6 = T0/2 ) &lt;br&gt; ( S2 = T1 + T0/2 )</td>
</tr>
<tr>
<td>4</td>
<td>( S1 = T0/2 ) &lt;br&gt; ( S3 = T1 + T0/2 ) &lt;br&gt; ( S5 = T1 + T2 + T0/2 )</td>
<td>( S4 = T1 + T2 + T0/2 ) &lt;br&gt; ( S6 = T2 + T0/2 ) &lt;br&gt; ( S2 = T0/2 )</td>
</tr>
<tr>
<td>5</td>
<td>( S1 = T2 + T0/2 ) &lt;br&gt; ( S3 = T0/2 ) &lt;br&gt; ( S5 = T1 + T2 + T0/2 )</td>
<td>( S4 = T1 + T0/2 ) &lt;br&gt; ( S6 = T1 + T2 + T0/2 ) &lt;br&gt; ( S2 = T0/2 )</td>
</tr>
<tr>
<td>6</td>
<td>( S1 = T1 + T2 + T0/2 ) &lt;br&gt; ( S3 = T0/2 ) &lt;br&gt; ( S5 = T1 + T0/2 )</td>
<td>( S4 = T0/2 ) &lt;br&gt; ( S6 = T1 + T2 + T0/2 ) &lt;br&gt; ( S2 = T2 + T0/2 )</td>
</tr>
</tbody>
</table>

Assuming that is desired to produce a balanced system of sinusoidal phase voltages, it is known that the corresponding space vector locus is circular.
Imposing $\tilde{V}_{\text{ref}} = |\tilde{V}_{\text{ref}}|e^{j\omega t} = |\tilde{V}_{\text{ref}}|(\cos \omega t + j \sin \omega t)$, where $|\tilde{V}_{\text{ref}}|$ is the magnitude and $\omega$ is the angular frequency of the desired phase voltages, it follows from eq. 3.18 that

$$
\begin{align*}
\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} &= \frac{\sqrt{3}}{2} \frac{|\tilde{V}_{\text{ref}}|}{V_{\text{dc}}} T_S \begin{bmatrix} \sin \frac{k\pi}{3} \\ -\sin \frac{(k-1)\pi}{3} \end{bmatrix} - \begin{bmatrix} -\cos \frac{k\pi}{3} \\ \cos \frac{(k-1)\pi}{3} \end{bmatrix} \begin{bmatrix} \cos \omega t \\ \sin \omega t \end{bmatrix}
\end{align*}
$$

(4.36)

while $0 \leq \omega t \leq \pi/3$ the reference vector lies in sector 1 and eq 3.36 reduces to

$$
\begin{align*}
\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} &= \frac{\sqrt{3}}{2} \frac{|\tilde{V}_{\text{ref}}|}{V_{\text{dc}}} T_S \begin{bmatrix} \sin \frac{\pi}{3} \\ \sin \omega t \end{bmatrix}
\end{align*}
$$

(4.37)

One of the important advantages of the space vector PWM over the sine-triangle PWM is that it gives nearly 15% more output voltage. Space vector modulation can also be regarded as the as a carrier based PWM technique with the modification that, the reference waveform has triplen harmonics in addition to the fundamental.

The conventional implementation of the space vector PWM involves the following steps:

1. Sector identification
2. Calculation of the active vector switching time periods $T_1$ and $T_2$.
3. Translation of the active vector switching time periods $T_1$ and $T_2$ into the inverter leg switching timings $T_{ga}, T_{gb}$ and $T_{gc}$.
4. Generation of the gating signals for the individual power devices using the inverter leg switching timings $T_{ga}, T_{gb}$ and $T_{gc}$.

4.9 Optimal power point tracking for Boost converter and three phase PWM inverter using MATLAB/SIMULATION

Comprehensive simulation studies were made to investigate the influence of a boost converter and space vector pulse width modulation based inverter as an intermediate maximum power point trackers for the PV supplied system. As the studies mainly concentrate on maximum power operation of the PV cell, a simulated modeling was
developed in the MATLAB environment, for the PV supplied converter system employing the mathematical models developed in the preceding sections. The simulated dynamic maximum power point tracking characteristics of the Boost converter and space vector pulse width modulation based inverter are shown in this section.

The simulated waveforms for Inductor current and capacitor voltage waveforms of DC-DC Boost converter for maximum power point tracking are shown for $T_c=25^\circ C$ and $G=1000\,W/m^2$ and for $T_c=25^\circ C$ and $G=1600\,W/m^2$.

![Fig.4.49: Simulated Dynamic characteristics of inductor current to reach maximum power point](image)
Fig. 4.50: Simulated Dynamic characteristics of capacitor voltage to reach maximum power point.

Fig. 4.49 and 4.50 are the simulated waveforms for Inductor current and Capacitor voltage $T_c=25^\circ C$ and for $G=1000W/m^2$. It can be observed from the inductor current waveform that the dc-dc boost converter is tracking maximum current of $I_{mp}$ from the PV cell at this particular temperature and irradiance. The value of $I_{mp}$ is given from the neural network is given in table 3.1. The simulated waveforms of inductor current and capacitor voltage waveforms for $T_c=25^\circ C$ and $G=1600W/m^2$ are shown in fig.4.51 and 4.53. Fig.4.52 shows the simulated waveform for mppt using neural networks.
Fig. 4.51: Simulated Dynamic characteristics of inductor current to reach maximum power point

Fig. 4.52: Maximum Power Point Tracking Using Neural Networks

Fig. 4.53: Simulated Dynamic characteristics of capacitor voltage to reach maximum power point
Using the control technique discussed in previous sections of the inverter the simulated waveforms for the Inverter output line-to-line voltage for phase A, inverter output currents, and the phase currents across the filter inductor are shown in fig.4.54 for cell temperature of $T_c=25^\circ$C and for $G=1000\text{W/m}^2$.

**Fig4.54:**
(a) Inverter output line to line voltage
(b) Inverter output current
(c) Filter inductor current
4.11 Summary

A general descriptive study of grid-connected PV system is presented which includes: system concept, types, problems encountered, and technical interconnection standards requirements and benefits of grid connected PV system. The detailed analysis of power electronic devices of grid connected PV system, DC-DC Boost converter and SVPWM inverter, its model are presented.

The simulation results of the dc-dc boost converter and the ssvpwm based inverter are presented for the maximum power point tracking. The simulation waveforms of boost converter for different cell temperature and irradiance are presented and the comparison of neural network \( I_{mp} \) with the \( I_{PV} \) of PV cell for maximum power tracking(fig. 4.52). It can be observed that after sometime the \( I_{pv} \) is reaching steady state and becoming equal to \( I_{mp} \) of the neural network and we can come to the conclusion that the maximum power is extracted continuously from the PV array. The simulated waveforms for the ssvpwm based inverter are shown for cell temperature, \( T_c=25^\circ C \) and for \( G=1000W/m^2 \).