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Dispersive Generation and Utility Connected Converters

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Abstract: ***The integration of the DG with the utility distribution network offers a number of technical, environmental and economic benefits. It also gives a great opportunity for distribution utilities to improve the performance of networks by reducing its losses. The technical challenges associated with the DG can be subdivided into three categories, the system interface to the grid, operation and control of the DG and Planning and design. This work focuses on the first category and aims to investigate a SVPWM algorithm for high power voltage source three level neutral point clamped inverter with operation system in sinusoidal mode. These techniques provide the nearest switching vectors sequence to the reference vector and calculates the on-state durations of the respective switching state vectors. The proposed algorithm is simple and based on standard two-level inverter and its implementation.***

Keywords*:* dispersive generation; multi-level inverter; SVPWM;nearst three vectors

1. Introduction

In power systems, large power generation plants located at adequate geographical places produce most of the power which is then transferred toward large consumption center over long distance transmission lines. The system control centers monitor and control the system continuously to ensure the quality of the power, namely the frequency and the voltage. However the power system is changing, a large number of dispersed generation (DG) units, including both renewable and nonrenewable sources such as wind turbines, wave generators, photovoltaic (PV) generators, small hydro, fuel cells and gas/steam powered combined heat and power (CHP) stations are being developed [1]–[3]. A wide spread use of renewable energy sources in distribution networks and a high penetration level will be seen in the near future. E.g., Denmark has a high penetration (20%) of wind energy in major areas of the country and today 14% of the whole electrical energy consumption is covered by wind energy. The main advantages of using renewable sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However the main disadvantage, apart from the higher costs e.g. photovoltaic is the uncontrollability. The availability of renewable energy sources has strong daily and seasonal patterns. But the power demand by the consumers could have a very different characteristic. Therefore it would be difficult to operate a power system installed with only renewable generation units due to the characteristic differences and the high uncertainty of the availability of the renewable sources. The way of fully exploiting the renewable energy is the grid connection normally at distribution level.

In conventional generation stations, the generators operate at a fixed speed and thereby with a fixed grid-frequency, however the dispersed generation presents a quite different and challenging picture. For example the voltage generated by variable speed wind power generators, PV generators and fuel cells cannot be directly connected to the grid. The power electronics technology plays a vital role to match the characteristics of the dispersed generation units and the requirements of the grid connections including frequency, voltage, control of active and reactive power, harmonic minimization etc. Power electronics being the technology of efficiently converting electric power plays an important role in the field of modern electrical engineering [4], [5], it is an essential part for the integration of dispersed generation unit to achieve high efficiency and performance in power systems.

2. Material & Methods

A. General Structure

The general structure for distributed systems is composed of an input power which is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network as shown in Fig. 1.

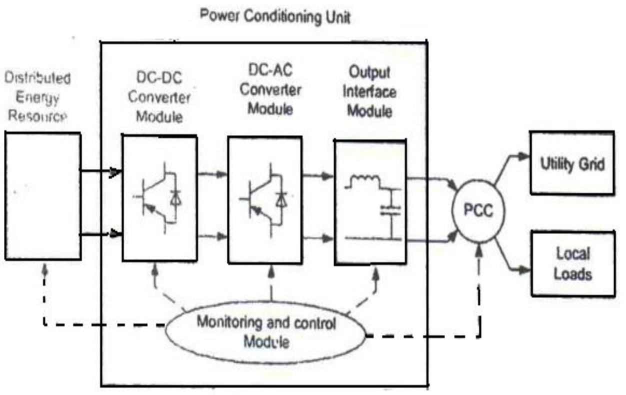


Figure 1: Various components of typical control system of DG The wind

Farms may be connected into different types of configurations with various control and compensation arrangements. For example ac local network with centralized compensation or with a dc transmission system and dc local network, decentralized control with a dc transmission system.

The power electronic based ASVC controls the reactive power of the wind farm and therefore the system voltage as shown in Fig. 2. It is noted that for the wind turbines directly connected to the ac grid without power electronic interface the real power cannot easily be controlled without a pitch control mechanism or dumping devices

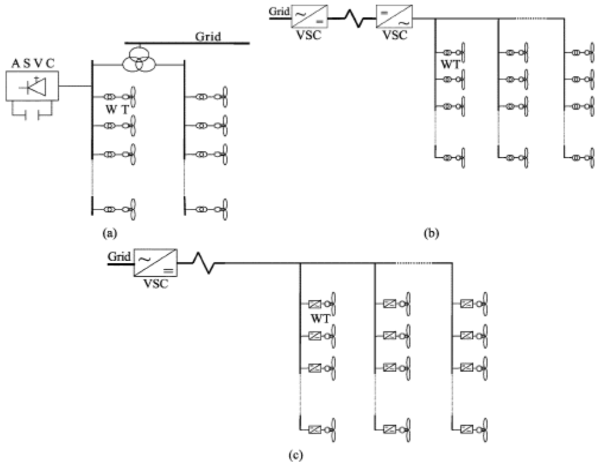


Figure 2: Wind farm arrangements: (a) a wind farm with an ASVC unit (b) a wind farm with a VSC based HVDC transmission and common ac-grid and (c) a wind farm with an internal dc network and individual power control

The fuel cell is a chemical device which produces electricity directly without any intermediate stage and has recently received much attention. The most significant advantages are low emission of green house gases and high power density. For example a zero emission can be achieved with hydrogen fuel. The emission consists of only harmless gases and water. The noise emission is low.

The power conditioning circuit of a fuel cell system often consists of a dc/dc converter and a dc/ac inverter as shown in Fig. 2(a). Another possible configuration of the system includes a dc/ac converter which converts the voltage into a high-frequency ac voltage then a cycloconverter is used to change the high frequency voltage into a power-frequency ac voltage as shown in Fig. 2(b).

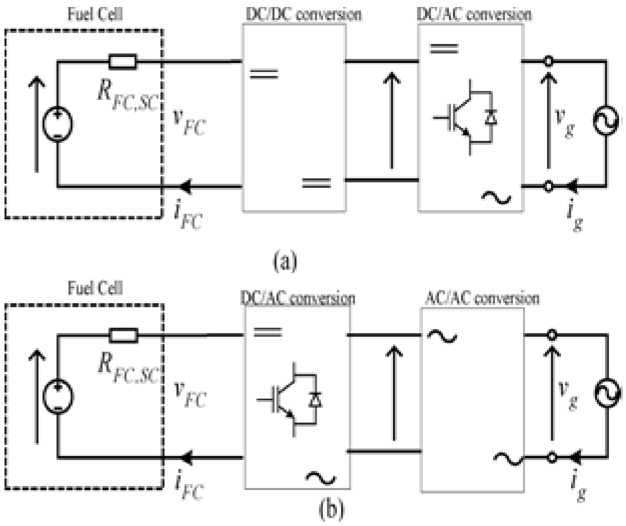


Figure 3: Schematics of fuel cell power electronic conditioning systems. (a) dc/dc, dc link, and dc/ac conversion and (b) dc/ac, ac link, and ac/ac conversion

The PV cell is an all-electrical device which produces electrical power when exposed to sunlight and connected to a suitable load. Without any moving parts inside the PV module the tear-and-wear is very low. Thus lifetimes of more than 25 years for modules are easily reached. However the power generation capability may be reduced to 75 ~ 80% of nominal value due to ageing. The power electronic interface for PV systems has two main tasks, one is to convert the generated dc voltage into a suitable ac current for the utility and other is to control the terminal conditions of the PV module(s) so as to track the Maximum Power Point (MPP) for maximizing the energy capture. In general three types of grid connected PV system configurations has been identified, centralized Inverters, String Inverters and two Stage Topologies for a Single Module as shown in Fig.4.

Multilevel inverters [6] are being increasingly used in high power medium voltage applications due to their compatibility for medium voltage and improved output performance at that voltage as compared to two-level inverters. Among various modulation techniques [6] for a multilevel inverter Space Vector PWM (SVPWM) is an attractive candidate due to the following merits.

- It directly uses the control variable given by the control system and identifies each switching vector as a point in complex space.
- It is useful in improving DC link voltage utilization, reducing commutation losses and THD.
- It is suitable for DSP implementation and optimization of switching patterns as well.

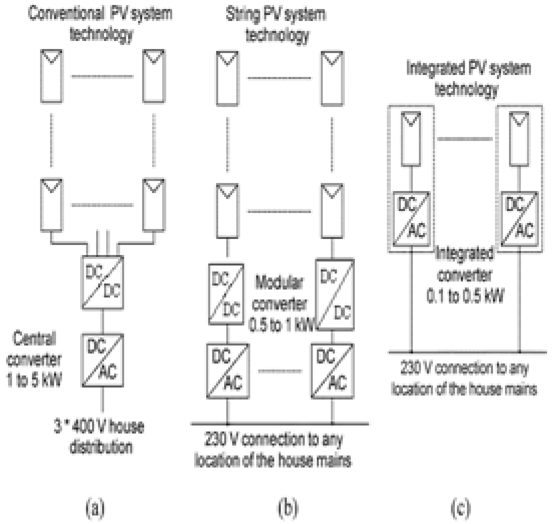


Figure 4: Configuration of PV systems: (a) centralized scheme, (b) string technology, and (c) modular concept

B. 3-level Voltage Source Inverter Topology

In recent years industry has began to demand higher power equipment which now reaches the megawatt level. Controlled ac drives in the megawatt range are usually connected to the medium voltage network. Today it is hard to connect a single power semiconductor directly to medium voltage grid [6]. For these reasons a new family of multilevel inverters has emerged as the solution for working with higher voltage levels [6], [7], [8], [9], [10]. Multilevel inverters include an array of power semiconductor and capacitor voltage sources the output of which generated voltages with stepped waveforms. The commutation of the switches permits the addition of the capacitor voltages which reach high voltage at the output while the semiconductors must withstand only reduced voltages. Fig.5 shows a schematic diagram of one phase leg of inverters with different numbers of levels for which the action of the power semiconductor is represented by an ideal switch with several positions.

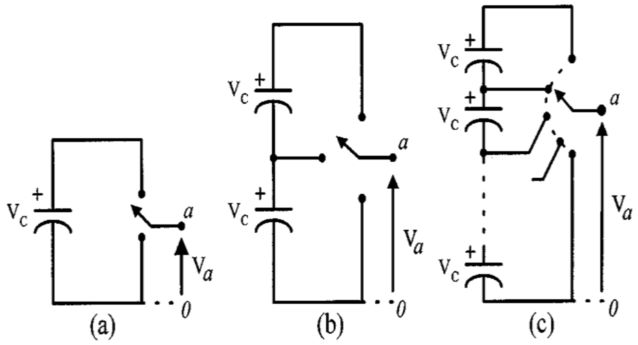


Figure 5: One phase leg of an inverter with (a) two levels (b) three levels and (c) n levels.

$n_{sw} = N^{ph}$ (1)

With N being the number of voltage levels in the dc link and ph being the number of phases.
Three different topologies have been proposed for multilevel inverters:

- Diode clamped (neutral clamped).
- Capacitor clamped (flying capacitor).
- Cascaded multicell with separate dc sources.

The most attractive features of multilevel inverters are as the follows.

- Blocking voltage of each switching device is clamped to the level of Vdc/(n-1) of DC-link voltage.
- They can generate output voltages with extremely low distortion and lower $\frac{dv}{dt}$
- They draw input current with very low distortion
- They generate smaller common-mod (CM) voltage thus reducing the stress in the motor bearing.
- They can operate with a lower switching frequency.

On the other hand this topology also has its disadvantages.

- Multi-Level VSI's require a high number of devices.
- The complexity of the controller is significantly increased.
- The balanced of the neutral-point has to be assured.

Since it's introduction in 1981, the three-level neutral point clamped (NPC) voltage source inverter Fig.6 has been shown to provide significant advantages over the conventional two-level VSI or high-power applications.

The three-level VSI was first considered with respect to high capacity high-performance ac drive applications. To this day it remains the area where this topology is most widely used. Other interesting applications of this technology include static VAR compensation systems, HVDC transmission systems, active filtering applications, as well as applications in power conditioning systems for superconductive magnetic energy storage (SMES). The neutral-point (NP) voltage balancing problem of three-level NPC VSI's has been widely recognized in literature [11], [12], [13]. Various strategies have been presented and successful operation has been demonstrated with a dc-link voltage balance maintained. In addition some of the proposed algorithms avoid the narrow pulse problem, minimize losses by not switching the highest current or share the balancing task with front-end converters as in [11].

The main modulation task is to achieve control of the system by switching converter power components i.e. determining which discrete vectors should be applied and for how long within a switching period. A typical modulation provides average voltage value equal to the voltage reference thus making a direct dc-ac conversion. There is also another yet less common control approach called direct (or modulation control) where discrete voltages are chosen directly from the state of the control variable. The examples of the second concept are direct torque control in the area of drives and direct power control for grid-connected applications.

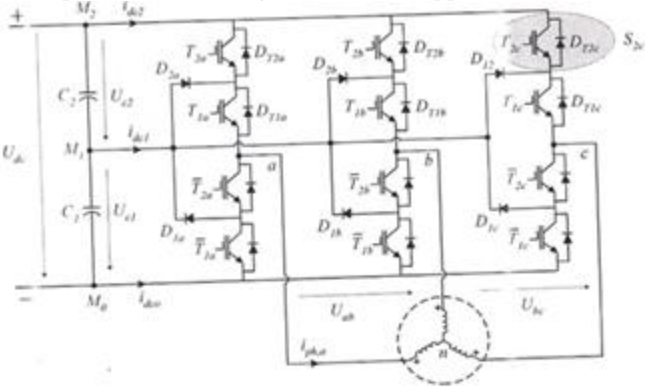


Figure 6: Three-level neutral point clamped inverter topology

For both approaches the demands for a modulation can be classified in two priority levels which may vary depending on the application. Due to capacitor voltage balancing and also high voltage stress on the clamping diodes with a number of levels larger than three the diode-clamped converter implementation has been mostly limited to three-levels. In this case the converter is usually called Three-Level Neutral Point Clamped Voltage Source Converter (3L-NPC VSI). One phase leg consists of 2(N-1) active switches and (N-1) (N-2) clamping diodes where N is the number of voltage levels. The total dc bus voltage U_{dc} is distributed across the dc capacitors. The key components that distinguish this circuit from a conventional two-level inverter are D_1 and D_2. These two diodes clamp the switch voltage to a half the level of the dc-bus voltage.

Table 1: Switch positions for one phase of the three-level NPC VSC

State	S_{1x}	S_{2x}	$\bar{S}_{1x}$	$\bar{S}_{2x}$
Positive "+"(v_{an}=+V_{dc}/2)	1	1	0	0
Zero"0"(v_{an}=0)	1	0	0	1
Negative"-"(v_{an}=-V_{dc})	0	0	1	1

Multi-level converters are becoming more attractive in high voltage and high efficiency applications. Because of their multi-step output voltage waveforms and the total harmonic distortion (THD) of the multi-level converter voltages is relatively low compared to the 2LVSC. However the number of voltage levels is limited by its control complexity, complication of the system structure, cost and conduction losses. Due to the emergence of high-voltage power devices such as IGCT or IGBT commercially available a general trend of replacing GTO-CSI by neutral –point clamped (NPC) VSI in both active and reactive high power applications came forth. The 3L-NPC VSC realizes minimum losses for constant carrier frequency and installed switch power. Furthermore it enables the highest possible carrier frequency for a given expense of semiconductor and converter output power. In this work we use Three-phase three-level neutral point clamped converter.

In order to produce three levels, the switches are controlled so that only two of the four switches in each phase leg are turned on at any time. In summary each phase node (a, b, or c) can be connected to any node in the capacitor bank (M0, M1, and M2). Thus the number of different converter switch states calculates to

$$n_{sw} = N^{ph} = 3^3 = 27 \qquad (2)$$

The operation of each switching inverter leg can be represented by three switching states P (1), O (0) and N (-1) as listed in table 1.

Based on their magnitude (length), the voltage vectors can be divided into four groups:

- Zero vectors (V_0), represented three switching states (1,1,1), (0,0,0) and (-1,-1,-1). The magnitude of V_0 is zero.
- Small vectors (V_1, V_4, V_7, V_{10}, V_{13}, V_{16}) all having a magnitude of $V_d/3$. Each small vector has two switching states, one containing (P) and other containing (N) and therefore can be classified into P-type or N-type.
- Medium vectors (V_3, V_6, V_9, V_{12}, V_{15}, V_{18}) whose magnitude is $\sqrt{3}V_d/3$
- Large vectors (V_2, V_5, V_8, V_{11}, V_{14}, V_{15}) all having a magnitude of $2V_d/3$

Connection of the a-phase to junctions M_0 and M_2 can be accomplished by switching both transistors T_{1a} and T_{2a} either off or on. These states are the same as the two-level inverter yielding a phase voltage of U_{xM1} = Udc/2 or U_{xM1} = -Udc/2 assuming $U_{C2} = U_{C1}$ = Udc/2. The connection to the junction *M1* is accomplished by gating T_{1a} on and T_{2a} off. In this representation the labels T_{1a} and T_{2a} are used to identify the transistors as well as the transistor logic (1 = on and 0 = off). Since the transistors are always switched in pairs, the complement transistors are labelled $\overline{T_{1a}}$ and $\overline{T_{2a}}$ accordingly. In a practical implementation some dead time is inserted between the transistor signals and their complements meaning that both transistors in a complementary pair may be switched off for a small amount of time during a transition. However for this discussion here the dead time will be ignored

Space Vector PWM

Multilevel inverters are being increasingly used in high power medium voltage applications due to their compatibility for medium voltage and improved output performance at that voltage as compared to two-level inverters. Among various modulation techniques for a multilevel inverter Space Vector PWM (SVPWM) is an attractive candidate due to the following merits.

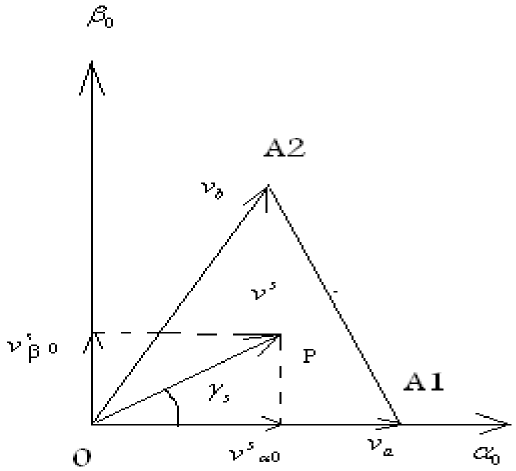
- It directly uses the control variable given by the control system and identifies each switching vector as a point in complex (α, β) space.
- It is useful in improving DC link voltage utilization reducing commutation losses and THD.
- It is suitable for DSP implementation and optimization of switching patterns as well.

SVM can be transformed into carrier-based PWM. Their difference is that the modulated waves of SVM are obtained by vectors calculation and the modulated waves of carrier-based PWM are pure sine wave or sine wave with common-mode injection. Therefore the modulated waves of SVM are more freedom which may include several independent modulated waves and additional switching can be added to reduce the output voltage's distortion. [14] Give Experimental comparison of carrier and space vector PWM for the three phase NPC converter according to neutral point balance and the output voltage spectrum. Many researches were done in the field of SV PWM [14]-[31]. Mondal [18] performs SVPWM on a 3-level inverter including operation in overmodulation range. The on time calculation equation differ for every triangle section at any modulation index. Seo [32] proposed a scheme for a three-level inverter based on two level SVPWM. The three level space vector diagram is divided into six two-level space vector diagram. This division is simple but cannot be directly applied to a n-level inverter. Mondal [26] use a neural-network based implementation of space vector modulation of a three-level voltage-fed inverter. The method has the fast implementation of an SVM algorithm, particularly when specific IC chip is used instead of a digital signal processor (DSP) but the on-time calculation change with position of reference. Seixas[27] proposed a technique in SV PWM to minimize the harmonics distortion of the output voltage. Busquets-Monge [31] give modulation approach based on the virtual space vector concept the solution based on requirement of the addition output currents equals zero.

In this work we use the methodology in [15]. This method provides a general solution and it can be easy extended to any level.

C. Modulation Principle

In this work a general space vector PWM scheme for multi-level has been proposed. The basic idea of space vector modulation is to compensate the required volt-seconds using discrete switching state and their on-times produced by an inverter. In two-level inverter, on-time calculation is based on the location of the reference vector within a sector S_i (i=1, 2, 3….6). For the geometry of the sector of the two-level shown in Fig.8 the on times calculated as :



$$v_a = (1,0), v_b = (0.5, h), v^s = (v_{\alpha 0}, v_{\beta 0})$$

Figure 7: Space vector diagram of first sector of two-level inverter

For a two-level inverter volt-second equation is

$$v^s T_s = v_a t_a + v_b t_b \quad (3)$$

The volt-second equation in terms of components of v^s, v_a and v_b along α_0 - β_0 axis, see Fig.4.

$$v^s{}_{\alpha 0}\ T_s = t_a + 0.5 t_b \quad (4)$$

$$v^s{}_{\beta 0} = h t_b \quad (5)$$

$$T_s = t_a + t_b + t_0 \quad (6)$$

Solving (4)-(6), we obtain

$$t_a = T_S[v^s{}_{\alpha 0} - v^s{}_{\beta 0} / 2h] \quad (7)$$

$$t_b = T_S[v_{\beta 0}{}^S / h] \quad (8)$$

$$t_0 = T_S - t_a - t_b \quad (9)$$

Where h = $\dfrac{\sqrt{3}}{2}$ is the height of a sector S_i which is an equilateral triangle of unity side.

D. Block Diagram of Modulation

The block diagram in Fig.8 explains the method to generate the switching signals. It consists of two basic units namely Pre-modulation Unit and Output Unit respectively. The Output Unit consists of two subunits namely calculation of inverter state time and generation of switching signals Unit and Mapping and Switching Signals Firing Unit.

The pre-modulation unit does two main task:

(a) Determination of coordinates ($v^s{}_{\alpha 0}$, $v^s{}_{\beta 0}$) of the small vector v^s

(b) Determination of the sector S_i and position within the sector in which the small vector is placed.

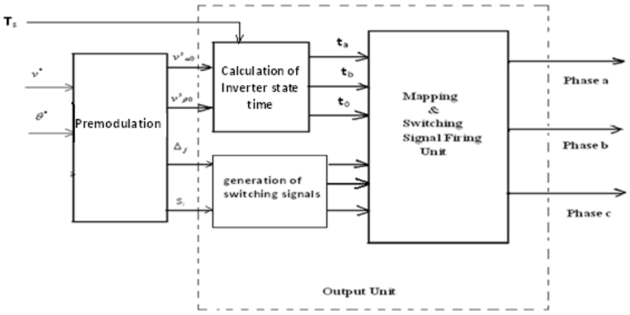


Figure 8: Block Diagram of Modulation process

Input to the pre-modulation unit is voltage reference v* sampling period T_s and θ^* **.** Calculation of inverter state time provides the on-times t_o, t_a, and t_b using **(7)**-(9) for the vectors that are vertices of the triangle in which the small vector is placed. Mapping and switching signal firing unit generates switching signals for the 3-phase inverter based on sector S_i, triangle Δ_j and on-times.

For any position of the reference vector we determine the sector of operation

S_i ($1 < S_i < 6$) and its angle ($0 \le \gamma \le 60$) within the sector by (10) and (11) respectively.

S_i = int(θ/60) + 1 (10)

γ = rem(θ/60) (11)

Where θ ($0 \le \theta \le 360$) is the angle of the reference vector with respect to the α-axis.

E. Sequence of Voltage Vector

In order to control the neutral point DC voltage both middle voltage vectors which output the same line to line voltages have to be selected in the time interval T. In spite we used dc source instead of capacitor in dc link. Fig.9 represent the flowchart of calculation of on times, sector and position of reference vector. Fig.10 shows the space vector representation of the output voltages. Table 2 shows the relation between the voltage vectors in sector 1 and the switching states of each phase. The sequence of the voltage vectors for sector one is obtained as shown in fig. 12 for the other sectors we do the same methodology.

Table 2: Switching states of the voltage vectors for sector 1

		a	b	c
V_0	V_{0n}	-1	-1	-1
	V_{00}	0	0	0
	V_{0p}	1	1	1
V_{16}	V_{16n}	1	1	0
	V_{16p}	0	0	-1
V_{17}		1	1	-1
V_{18}		1	0	-1
V_1	V_{1n}	1	0	0
	V_{1p}	0	-1	-1
V_2		1	-1	-1

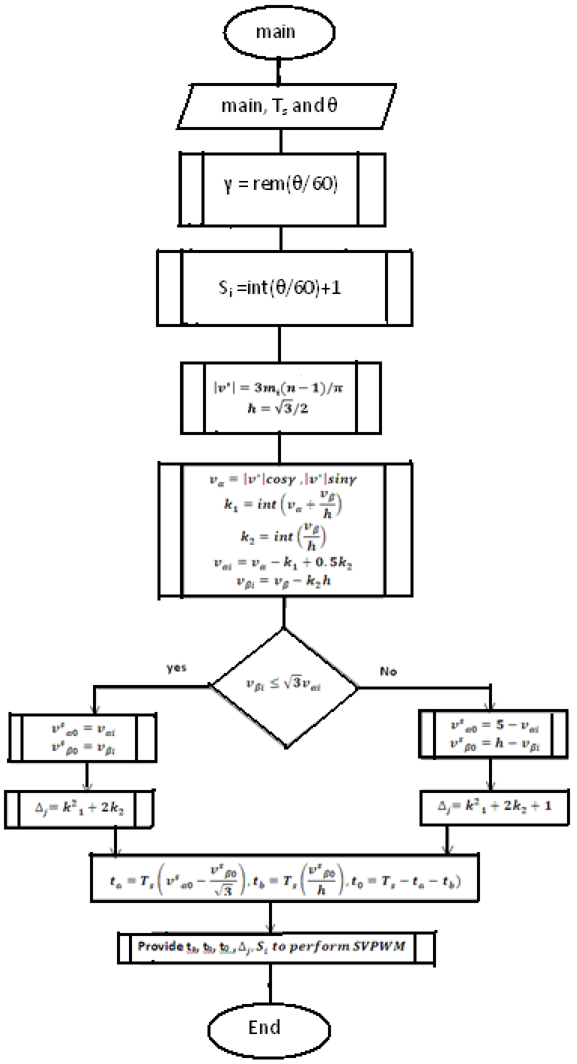


Figure 9: Flowchart of the Calculation of the system parameters

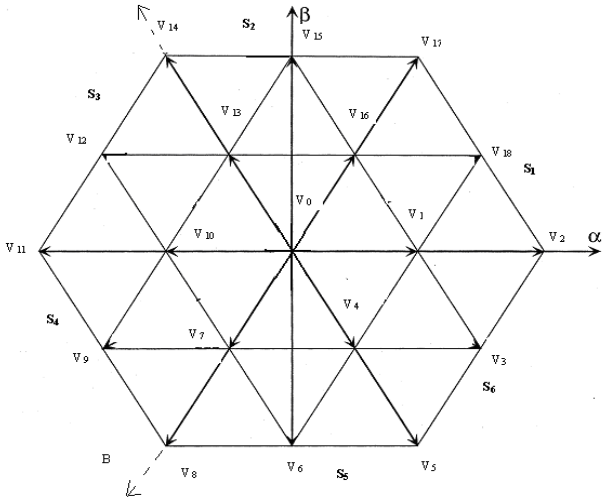
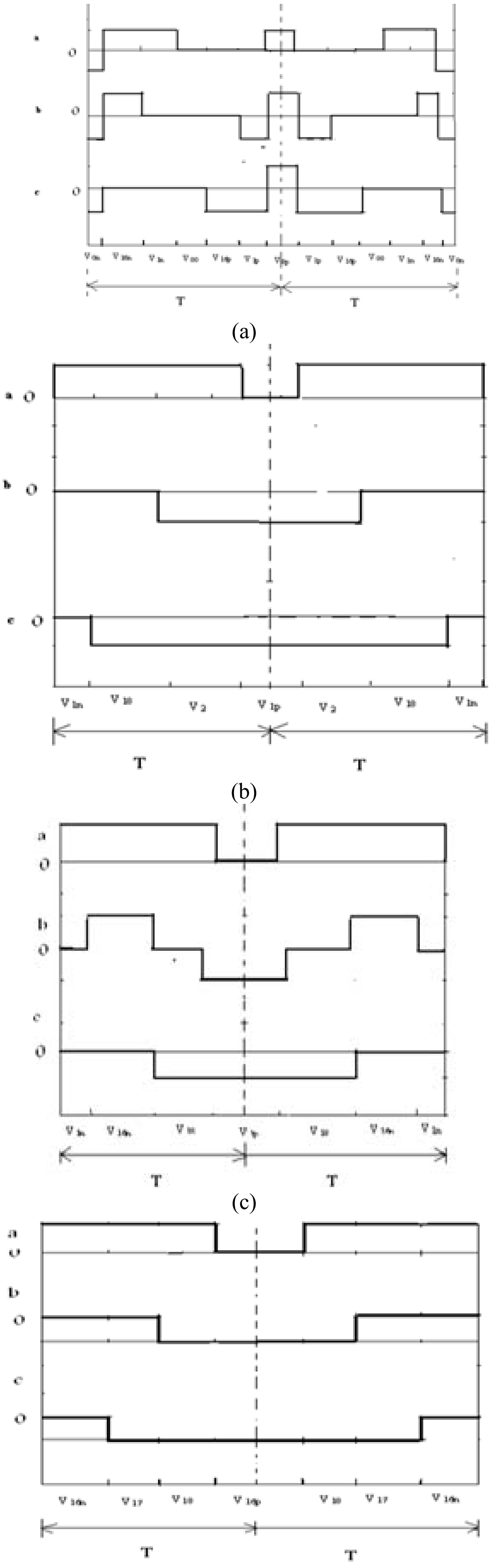


Figure 10: Space vector representation of the output



(a)

(b)

(c)

(d)

Figure 11: Switching sequence of triangles in sector 1 `(a) triangle 0 (b) triangle 1 (c) triangle 2 (d) triangle 3

F. Propose Scheme for Multi-level Inveretrs Grd Connected

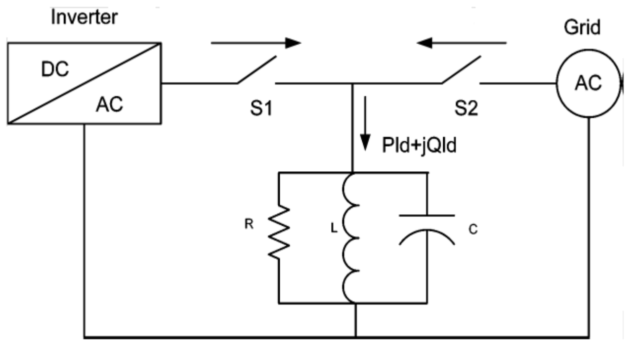


Figure 12: Possible isolation of grid to supply local load alone

When the inverter is supplying the local load alone, then the input controller, which normally tracts the maximum power which can be produced by the DG unit, has to be modified. In such a case the maximum active power and reactive power is dictated by the load supplied by the inverter, provided the DG-Inverter set has enough capacity. Otherwise some load shedding is necessary in order to satisfy the input and output power balance.

If the inverter is supplying only an isolated load, then the required control apparatus is much simplified, because there are no synchronization problems, and the whole arrangement becomes similar to an uninterruptible power system (UPS). The rms voltage may also be controlled by a PI compensator. The output of the Compensator adjusts the modulation index of the 50 Hz sine PWM inverter driver. This type of simple control provides stable output in the steady state, but transient performance may not be adequate for aggressive load transients [36], such as starting of compressor-driven loads. Instantaneous voltage control provides more reliable control during transients. It is more difficult to design the compensator which would work properly at both steady state and transient operations.

The general structure for Distributed Generation systems is composed of an input power which is transformed into electricity by means of a power conversion unit, whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network, as shown in Fig.12.

3. Results and Discussions

Fig. 13 shows simulink representation of the inverter connected to DC link.

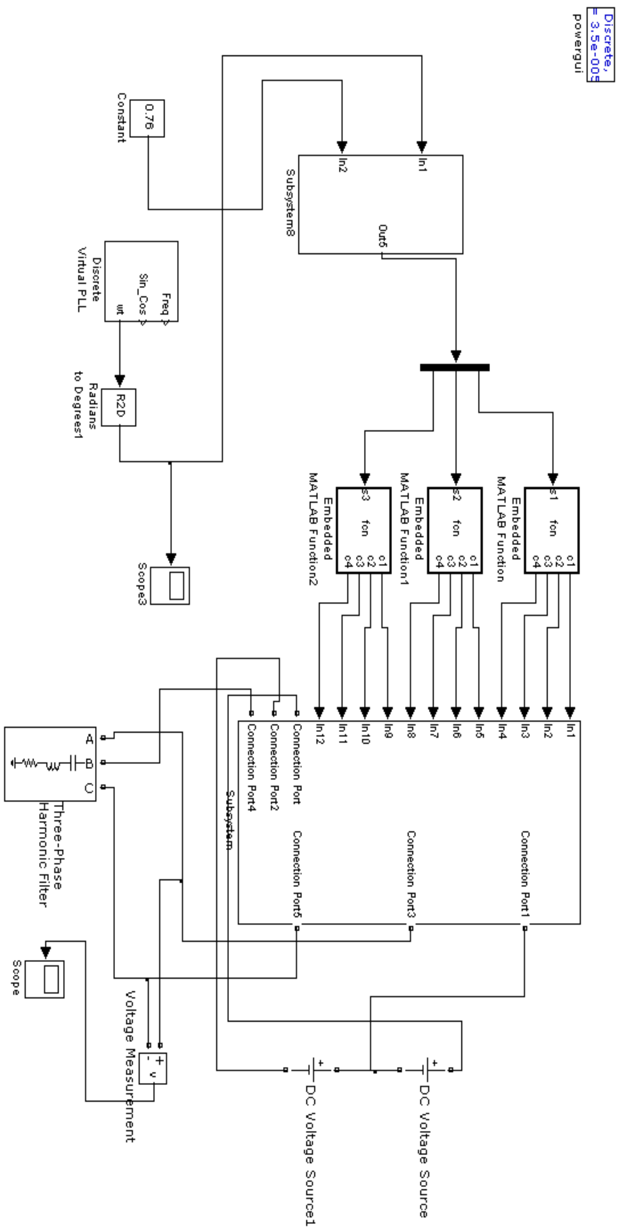


Figure 13: Simulink representation of the inverter connected to DC link

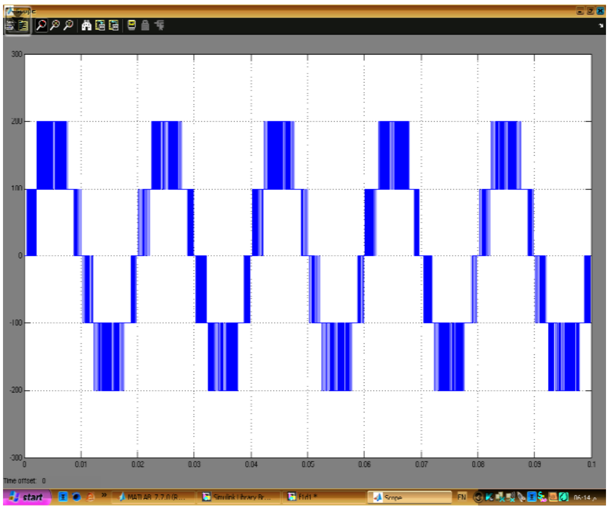


Figure 14: output voltage of the inverter V_{dc}=200 V

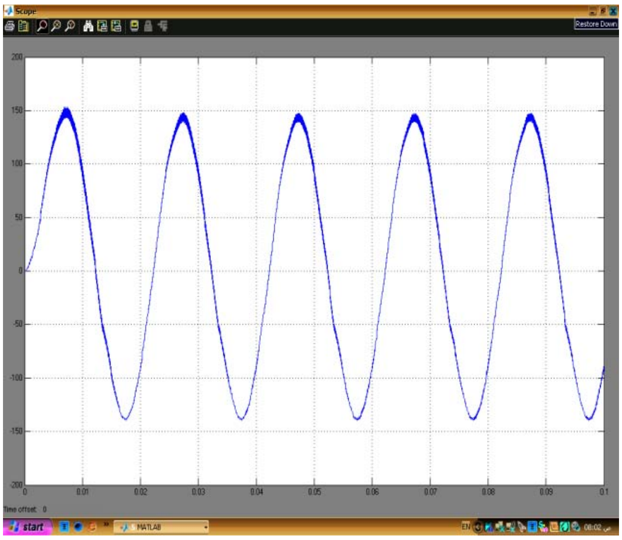


Figure 15: output voltage of the inverter m=0.84, V_{dc}=200 V

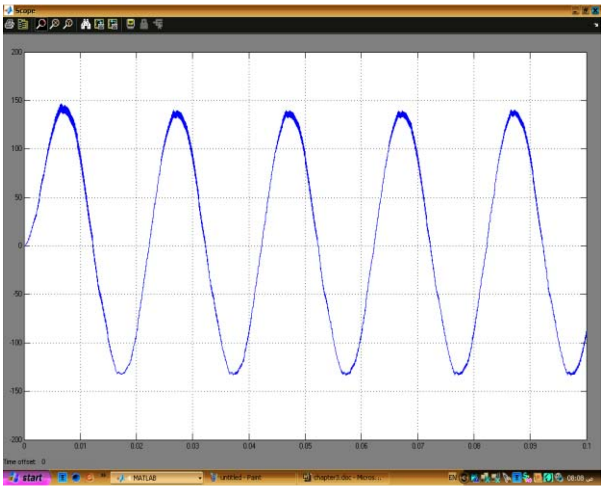


Figure 16: output voltage of the inverter m=0.76, V_{dc}=200 V

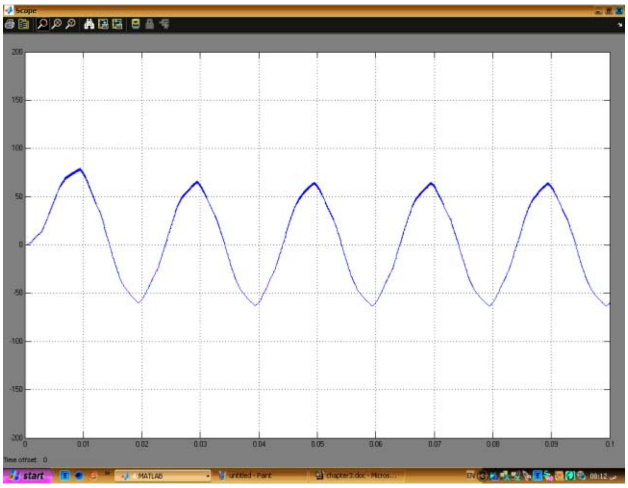


Figure 17: output voltage of the inverter m=0.6, V_{dc}=200 V

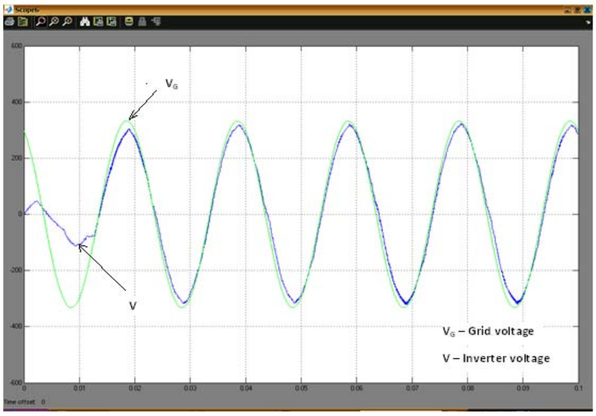


Figure 18: Output voltage of inverter and the grid voltage when the frequency and phase angle is $f_g = 50$ Hz , $\theta_g = 0$

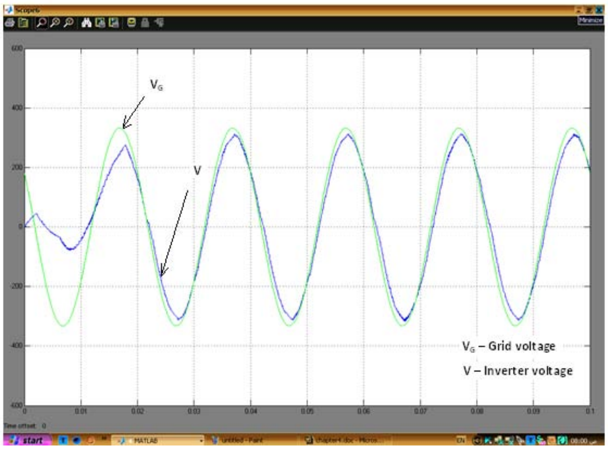


Figure 19: Output voltage of inverter and the grid voltage when the frequency and phase angle is $f_g = 50$ Hz , $\theta_g = \frac{\pi}{6}$

Figures from (14) to (16) show resulting output line voltage of the inverter using the algorithm shown in the flow chart in fig.9 and schematic block diagram in Fig.8. The algorithm has been developed on matlab/simulink. The DC Link voltage is 200 V, reference frequency 50 Hz and sampling frequency is 5 kHz. Fig.14 shows the line voltage of inverter without any load filtering. The modulation index in his case is 0.84. Fig.15 represent the same voltage but after using filter. Fig.16 and

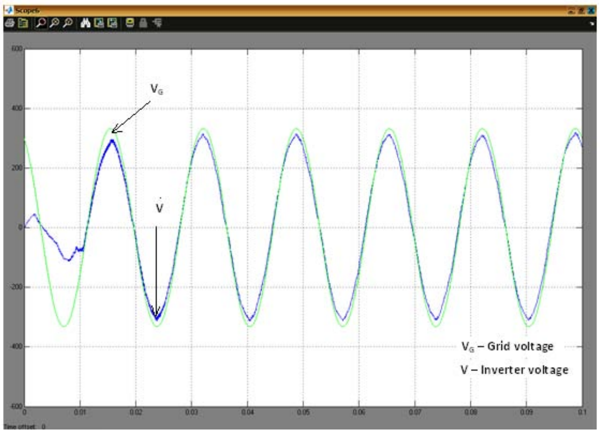


Figure 20: Output voltage of inverter and the grid voltage when the frequency and phase angle is $f_g = 60$ Hz , $\theta_g = \frac{2\pi}{3}$

Fig.17 show output line voltage with different modulation index. From figures we see that we can varies the magnitude of output inverter voltage by vary the reference input signal of the modulation index. Fig.18, Fig.19 and Fig.20 represent the output voltages of the inverter and reference input voltage with different phase angle and frequency .

4. Conclusion

Most manufacturers use two-level pulse width modulation (PWM) voltage-source inverters (VSI) because this is the state-of-the-art technology used for wind systems. The possibility of high switching frequencies combined with proper control circuits makes these converters suitable for grid interface in the case of distributed generation, which may also have a large contribution to the improvement of generated power quality. Three-level neutral-point-clamped VSI is an option for high power systems to avoid the necessity for using high-voltage power devices.

This work involves the design of an interactive inverter which could either be sine PWM driven or of space vector configuration. The inverter could also be 2-level or multilevel. The latter type enables the operation at higher voltage for the same switching device operating voltage rating. This is very important, because dispersive generation applications are expanding rapidly, and higher power ratings necessitates the use of higher voltages in the inverter. This method is simple and with help of reference voltage and phase angle we can easily control and synchronize the DG with utility

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