

Review

# Digital Control Techniques Based on Voltage Source Inverters in Renewable Energy Applications: A Review

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**Abstract:** In the modern era, distributed generation is considered as an alternative source for power generation. Especially, need of the time is to provide the three-phase loads with smooth sinusoidal voltages having fixed frequency and amplitude. A common solution is the integration of power electronics converters in the systems for connecting distributed generation systems to the stand-alone loads. Thus, the presence of suitable control techniques, in the power electronic converters, for robust stability, abrupt response, optimal tracking ability and error eradication are inevitable. A comprehensive review based on design, analysis, validation of the most suitable digital control techniques and the options available for the researchers for improving the power quality is presented in this paper with their pros and cons. Comparisons based on the cost, schemes, performance, modulation techniques and coordinates system are also presented. Finally, the paper describes the performance evaluation of the control schemes on a voltage source inverter (VSI) and proposes the different aspects to be considered for selecting a power electronics inverter topology, reference frames, filters, as well as control strategy.

**Keywords:** voltage source inverters (VSI); voltage control; current control; digital control; predictive controllers; advanced controllers; stability; response time

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## 1. Introduction

Nowadays, energy demand is getting increased with the passage of time and distributed generation (DG) power systems especially through wind, solar and fuel cells as well as their related power conversion systems are conferred immensely. Many problems like grid instability, low power factor and power outage etc. for power distribution have also been increased with increase in energy demand [1]. However, DG power systems are found to be a sensible solution for such problems as they have relatively robust stability and causes additional flexibility balance. Moreover, their utilization can also improve the distribution networks management and carbon release is also reduced. VSIs are extensively necessitated for the commercial purpose as well as for the industrial applications as they play a key role in converting the DC voltage and current, usually produced by various DG applications, into AC before being discharged into the grid or consumed by the load. Several control systems are introduced, various schemes are proposed and numerous techniques are updated in order to facilitate the control of three-phase VSI. The objectives of these control schemes are to constrain the high and low-frequency electromagnetic pollution and to inject the active power with zero power factor into the

grid [2]. The smooth and steady sinusoidal waveform can be a good input to a load for getting the most suitable response, therefore, the output of the inverter, which normally enjoys special standards and characteristics, should be controlled for providing an aforementioned waveform to load and grid.

Generally, it is observed that several problems are caused in linking the DG power system to a grid or grid to load in bidirectional inverters, i.e., grid instability, distortion in the waveform, attenuation as well as major and minor disturbances. Hence, in order to overcome these problems and to provide high-quality power, appropriate controllers with rapid response, compatible algorithm, ability to remove stable errors, less transit time, high tracking ability, less total harmonic distortion, THD value and smooth sinusoidal output should be designed. Various controllers are designed for achieving these qualities. The cascade technologies are introduced in the literature comprises of an inner current loop and outer voltage loop [3–12]. As the inner-loop current controller plays a fundamental role in closed-loop performance, various control approaches like PI [3–6],  $H_\infty$  [7,8], deadbeat [9–11,13] and  $\mu$ -synthesis [11] are extensively applied. Outer voltage loop in the aforementioned cases refines the tracking ability and decreases the tracking error. In case of no input limitations, aforesaid PI controllers are the best choice for stabilizing the inner loop performance. However, input constraints restrict their performance and no optimization is usually observed by using PI controllers. The deadbeat control method is proposed in [9] to enhance the closed-loop performance but unfortunately, it was found highly sensitive to the disturbances, parameters mismatches and measurement noise. Later on, some observed based deadbeat controllers are introduced in order to provide compensation for these discrepancies, however, a trade-off was observed between phase margin and closed-loop performance [9,10]. Afterwards,  $H_\infty$  controllers in [7,8] are offering robust output response instead of input constraints, however, guaranteeing only the local stability like the  $\mu$ -synthesis controller in [12].

Several other manuscripts are also amalgamated with literature for fulfilling the demand of electric power regarding fulfilling the environmental principles concerning green-house effects [14–18]. Various structures and topologies for interconnecting DGs are presented in [19–21] for parallel operation and in [22–24] for independent operation. For this reason, various control strategies are anticipated for stabilizing the system to control the voltage and frequency in case of unbalanced load and nonlinear loads. Many researchers have proposed several schemes for designing the controller in order to refine the quality of output voltage of DC to AC inverter. In [25], a control scheme is presented for a DG unit in islanded mode, this control technique is suitable for balanced load conditions for a DG unit when it is electronically coupled. However, this technique is constrained to small load variations and remain unable to stabilize the system in large load variations. A robust controller is proposed in [26] for balanced as well as unbalanced systems. However, it fails to address non-linear load properly. In [27], a repetitive control is implemented for controlling the inverters but the relatively slow response and absence of a systematical technique for stabilizing the error dynamics are the core problems. In [28], the uncomplicatedly designed controller is used to mitigate the load disturbances up to a significant extent through a feedforward compensation element, however, it is only restricted to balanced load conditions. In [29], a spatial repetitive control technique is implemented for controlling the current in a single-phase inverter. The results are satisfactory under non-linear load conditions; however, it is not guaranteeing the optimal tracking ability for a three-phase inverter. In [30], a discrete-time sliding mode current controller is proposed, it is optimally operating to control the system at a sudden load change, an unbalanced load and a nonlinear load, however, the system is quite intricate. In [31], the voltage and frequency controller is presented through a discrete-time mathematical model in order to operate the distributed resource units. This technique is achieving good voltage regulations under different load conditions but the results are not verified through the experimental setup. In [32], a controller is proposed having an adaptive feedforward compensation method applied through a Kalman filter for estimating the variation in parameters, the response was robust; however, tuning of covariance matrices are not appropriately described in the paper. In [33], a corresponding controller is recommended for distributed generation systems in grid applications, the anticipated controller is good in handling the grid disturbances and handling the nonlinearities, however, it is not suitable

in stand-alone mode due to the nonexistence of voltage loop. In [34,35], the adaptive controller is used and voltage tracking is achieved precisely. The system is guaranteed under systems parameter variations, however, complexity in computation exists and a certain pre-defined value is needed for parameters. In [36], an output voltage controller based on the resonant harmonic filters is presented. It measures the capacitor current and load current in the same sensor. Unbalanced voltage condition and harmonic distortion are compensated in this controller. However, THD value is not defined appropriately, therefore, it is complicated to assess the quality of the controller. An adaptive control technique based proportional derivative controller is presented in [37], for a pulse width modulated inverter operation in islanded distributed generation system, voltage regulation under numerous load conditions is evaluated, though it is not easy to achieve the suitable control gains as per the designing procedure specified in the paper. Moreover, voltage and frequency are optimally controlled, active and reactive power unbalancing is aptly compensated through small signal modeling of inverters in [38].

The key purpose of this study is to provide a comprehensive review of the digital control strategies for different types of three-phase inverters in stand-alone as well as grid-connected modes. Correspondingly, explanation, discussion and comparison of the various control strategies are described in this manuscript in detail.

The manuscript is organized as: classification of voltage source inverters is described in Section 2. Section 3 discusses the characteristics of control systems, followed by a depiction of reference frames in Section 4. The control strategy in decoupled dq frame and time-delay sampling scheme for VSI are depicted in Sections 5 and 6 respectively. An overview of the most commonly used filters and damping techniques is illustrated in Sections 7 and 8 respectively. The grid synchronization techniques followed by modulation techniques are described in Sections 9 and 10 of the manuscript, respectively. Moreover, control Techniques along with their pros. & cons. are described in Section 11. In Section 12, comparative analysis and future goals for the researchers are elaborated. Whereas, conclusions are drawn in Section 13.

## 2. Classification of VSIs

There are various types, in which the inverters are categorized. Figure 1 shows the complete detail of categories in which voltage source inverters are classified.

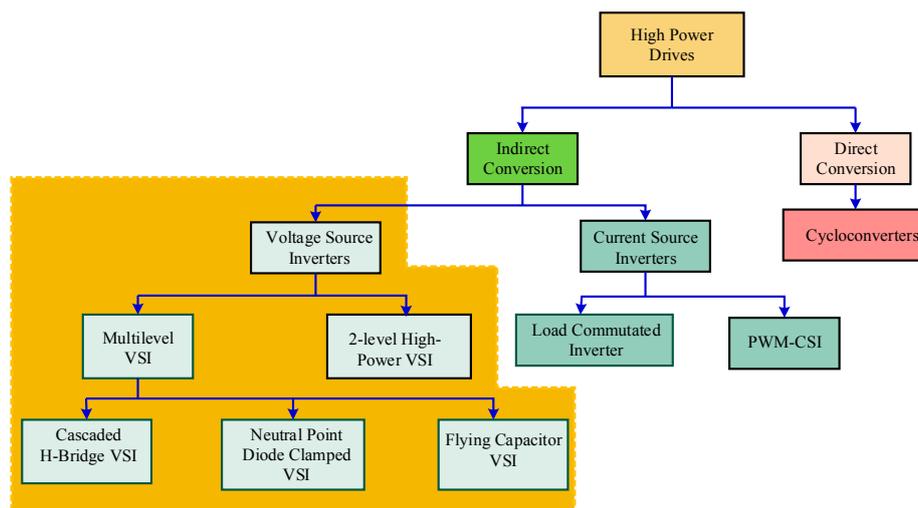
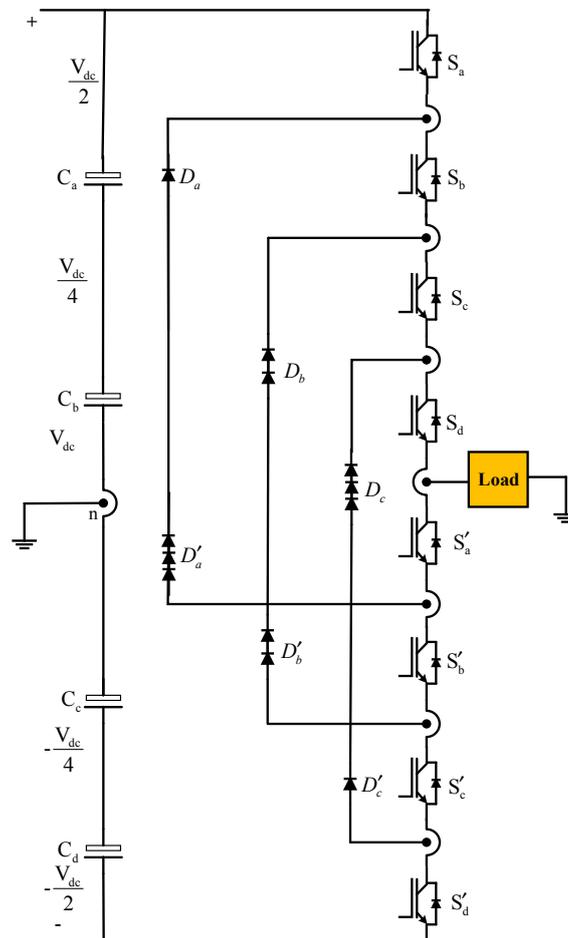


Figure 1. Classification of voltage source inverters (VSIs) in high power drives.

### 2.1. Multilevel Diode Neutral-Point Clamped Inverter

Multilevel inverter (MLI) was proposed in 1975, its design was like a cascade inverter with diodes facing the source. This inverter was later transformed into a Diode Clamped Multilevel Inverter,

which is also named as a Neutral-Point Clamped Inverter (NPC) [39]. In this type of multilevel inverters, the integration of voltage clamping diodes is indispensable. An ordinary DC-bus is separated by an even number of bulk capacitors connected in series with a neutral point in the middle of the line that is dependent on the voltage levels of the inverter. In Figure 2, a five-level NPC-MLI is shown, here the clamping diodes are interlinked to M-1 regulatory pairs if M is considered as voltage levels of the inverter.



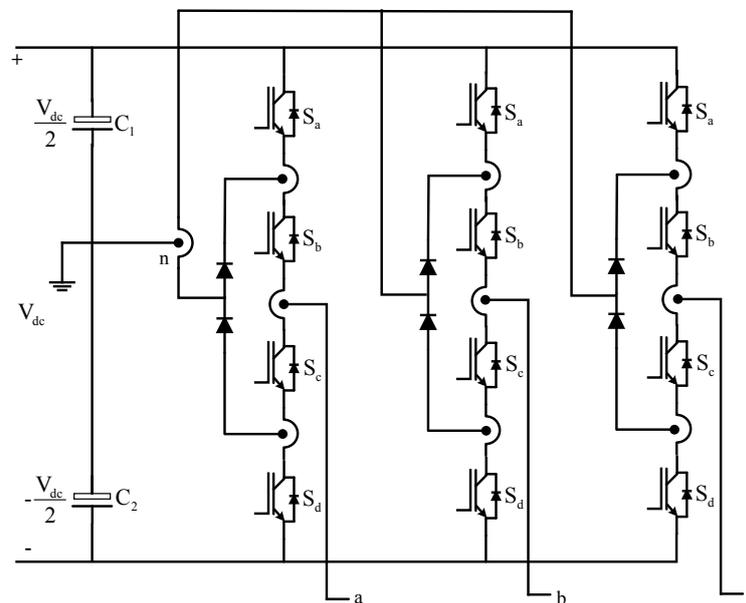
**Figure 2.** Five-level diode neutral-point clamped inverter.

The neutral point converter was designed by Nabae, Takahashi and Akagi in 1981, this was basically a three-level diode-clamped inverter [40]. A three-phase Three-level diode-clamped inverter is shown in Figure 3.

The NPC-MLI is considered as an important device in conventional high-power ac motor drive applications like mills, fans, pumps and conveyors, moreover, it also offers solutions for industries including chemicals, gas, power, metals, oil, marine, water and mining. The back-to-back configuration of inverters for regenerative applications is also considered as a major plus point of this topology, used, for example, in regenerative conveyors, mining industry and grid interfacing of renewable energy sources like wind power [41].

There are several benefits as well as drawbacks of multilevel diode-clamped [39,42]. A common dc bus is shared by all the phases, this results in the reduction of capacitance requirements of the inverter. Due to this reason, implementation of a back-to-back topology is not only credible but can also be applied practically for performing different operations in an adjustable speed drive and a high-voltage back-to-back inter-connection. The capacitors can be recharged as a group. On fundamental frequency, switching efficacy is relatively higher. However, real power flow is problematic in case of a single

inverter as the intermediate dc levels will tend to overcharge or discharge due to inappropriate monitoring and control. The number of clamping diodes are quadratically associated with the number of levels, which can be unwieldy for units with a high number of levels.



**Figure 3.** Three-level diode neutral-point clamped inverter.

## 2.2. Multilevel Capacitor Clamped/Flying Capacitor Inverter

A corresponding topology for the NPC-MLI topology is the Flying Capacitor (FC), or Capacitor Clamped, MLI topology, it is depicted in Figure 4. As an alternative to clamping diodes, capacitors are used for holding the voltages to the referred values. In the NPC-MLI,  $M - 1$  number of capacitors are integrated on a shared DC-bus, where  $M$  is the level number of the inverter and  $2(M - 1)$  switch-diode regulatory pairs are used. Though, for the FC-MLI, instead of clamping diodes, one or more capacitors are used to produce the output voltages depends upon the position and the level of the inverter. They are coupled to the midpoints of two regulatory pairs on the same position on each side of a midpoint [42], see capacitors  $C_a$ ,  $C_b$  and  $C_c$  in Figure 5.

The basic difference is the usage of clamping capacitors in place of clamping diodes, as using them increases the number of switching combinations as capacitors do not block reverse voltages [42]. Numerous switching states would be able to produce the same voltage level and the redundant switching states would also be available.

DC side capacitors in this topology have a ladder-like structure and the voltage on each capacitor deviates from that of the other capacitor. The voltage increment between two adjacent legs of the capacitors provides the size of the voltage steps in the output waveform. One advantage of the flying-capacitor-based inverter is the redundancies for inner voltage levels; i.e., two or more effective switching amalgamations can produce an output voltage.

Unlike the diode-clamped inverter, the flying-capacitor inverter never requires all of the switches to be on (conducting state) in a consecutive series. Moreover, the flying-capacitor inverter has phase redundancies, while the diode-clamped inverters have only the line-line redundancies [40]. These redundancies provide selective charging and discharging of specific capacitors and it can be incorporated in the control system for the voltage balancing across the various levels.

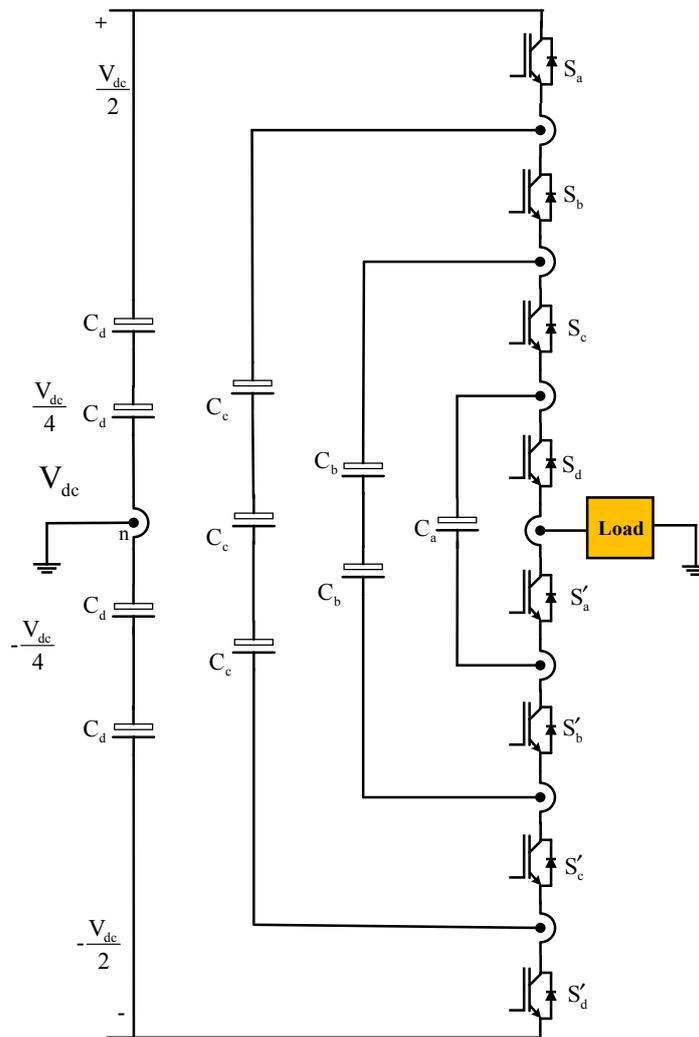


Figure 4. Multilevel (Five-level) capacitor clamped/flying capacitor inverter.

There are several advantages and disadvantages of multilevel flying capacitor inverters [41,43]. Phase redundancies are offered for balancing the voltage levels between the capacitors. Active and reactive power flow can be regulated. The presence of various capacitors allows the inverter to ride through outages for short duration and deep voltage sags. However, the control system is complex for tracking the voltage levels for all of the capacitors. Correspondingly, recharging all the capacitors to the same voltage level and startup are complex. Switching operation and efficacy are poor for real power transmission. The installation of large numbers of capacitors is not much economical and it also makes the system bulky as compared to the clamping diodes in multilevel diode-clamped converters. Likewise, packing is also tougher in the inverters with a higher number of levels. The five-level and three-level FC-MLIs are represented in Figures 4 and 5 respectively.

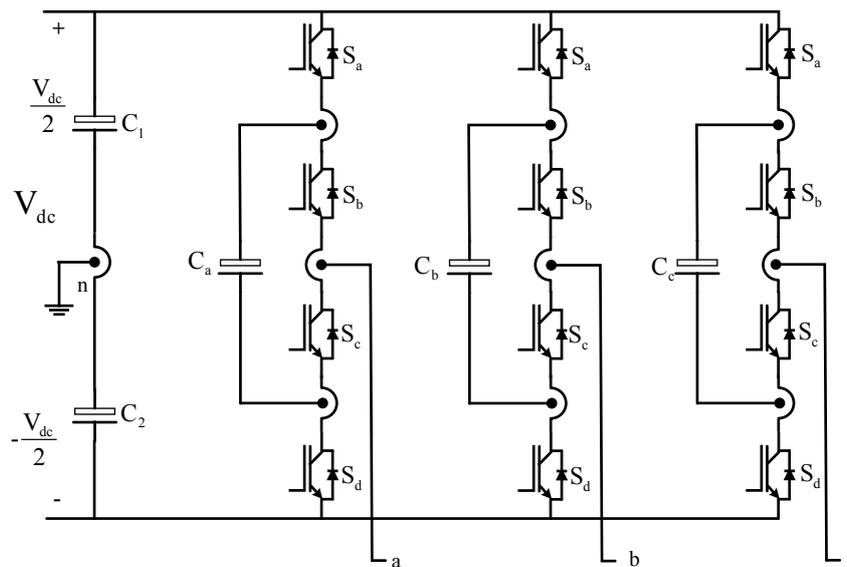


Figure 5. Three-level capacitor clamped/flying capacitor inverter.

### 2.3. Cascaded H-Bridge Inverter

There are minimum three voltage levels for a multilevel inverter using cascaded topologies. In order to attain a three-level waveform, a single full-bridge or H-bridge inverter is considered. Each inverter is provided with a separate DC source. A three-level cascaded inverter is shown in Figure 6.

By using different combinations of the four switches,  $S_a$ ,  $S_b$ ,  $S_c$  and  $S_d$ , each inverter level can produce three different outputs of voltage, i.e.,  $V_{dc}$ , 0 and  $-V_{dc}$  by connecting the dc source to the ac output.  $-V_{dc}$  can be obtained by turning on switches  $S_b$  and  $S_c$  whereas for obtaining  $V_{dc}$ , switches  $S_a$  and  $S_d$  can be turned on. However, for achieving the output voltage on 0 level either  $S_a$  and  $S_b$  or  $S_c$  and  $S_d$  can be turned on. The different full-bridge inverters must be connected in series in the way that the finally produced voltage waveform should be the sum of the inverter outputs. Multilevel cascaded inverters are proposed for the applications such as static VAR generation (reactive power control), an interface with renewable energy sources and for battery-based applications. The main reasons for preferring a cascaded multilevel H-bridge inverter are the availability of possible output levels more than twice the number of dc sources [42–44]. The series of H-bridges enables the manufacturing and packaging process more easy, quick and economical. However, the requirement of a separate dc source for each H-bridge constrains the applications of these inverters to the products having multiple separate DC sources already or readily available.

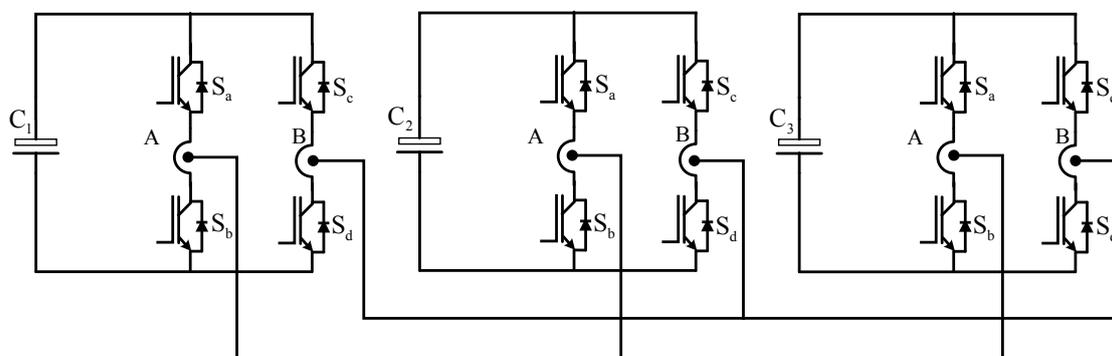


Figure 6. Cascaded H-bridge multilevel inverter.

#### 2.4. Two-Level Three Phase VSI with an Output Filter

A simple two-level inverter is used to convert dc to ac output. It consists of six switches, IGBTs and MOSFETs are the two most suitable switching components for these inverters. Due to simplicity in their structure and ability to handle the voltage by keeping the system stable, they are preferred utmost in the industry and for commercial purpose due to their support in uninterruptible power supply applications. These are usually connected to the load or the grid by using LC or LCL filter. Various types of control systems are implemented by the researchers to improve their performance, robustness and stabilization, compensating the power losses and lowering the THD value. SPWM or SVPWM are mostly applied to these types of inverters for getting appropriate values. Two level three phase VSI is shown in Figure 7. In Figure 7, the  $S_1$  to  $S_3$  and  $S'_1$  to  $S'_3$  shows the switches of the inverter. Whereas,  $u_c$  represents the voltage across the capacitors, C.

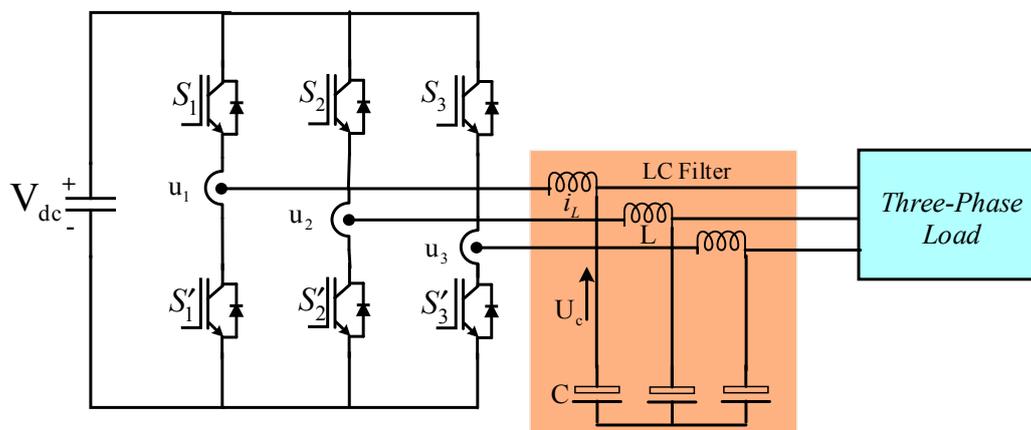


Figure 7. Two-level three phase VSI with an output LC filter.

#### 2.5. Three Phase Four-Leg VSI with an Output Filter

Nowadays, a growing interest in using the three-phase four-leg inverters is observed from the researchers' due to their ability to handle the unbalanced loads efficaciously in four-wire systems [45,46]. In this topology, the neutral point is proposed by connecting the neutral path to the mid-point of the additional fourth leg, as shown in Figure 8. In Figure 8,  $u_o$  represents the output voltage of the LC filter, whereas M represents the point neutral point between two switches,  $S_M$  and  $S'_M$ . Even though the configuration in this topology does not need expensive and large capacitors and produces lower ripple on the DC link voltage, however, using two extra switches lead to a complex control system [47]. Additionally, the split DC-link voltage is about 15% less as compared to the AC voltage in this configuration [48].

Another topology can be using split DC link, which is the most common way of providing a neutral point to three-phase VSIs. This configuration can be provided by using two capacitors i.e., splitting the DC-bus into two parts by using a pair of capacitors and by connecting a neutral path to the mid-point of these capacitors, as shown in Figure 9. Both these configurations have several advantages and disadvantages, however, the split dc-link is found unsuitable for handling the unbalanced loads, whereas, three-phase four leg inverter is found most appropriate for handling the non-linear and unbalanced load conditions. A comparison of different types of VSIs with respect to their characteristics, control contents and complexity is described in Table 1.

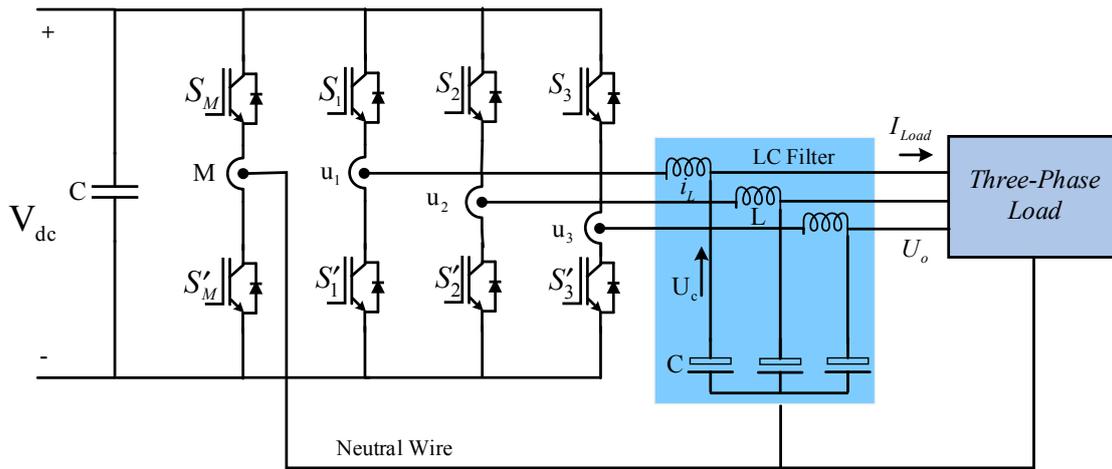


Figure 8. Three-phase four-leg inverter with an output LC filter.

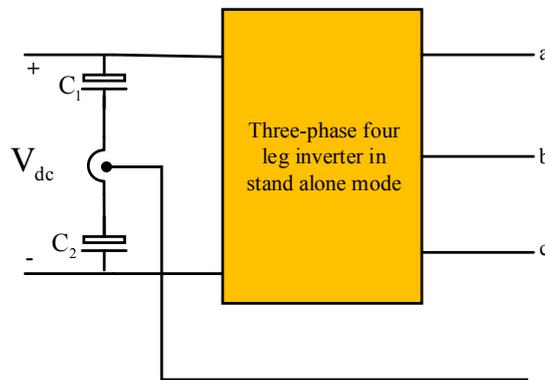


Figure 9. Schematic of a Three-phase four-leg inverter with split DC-link.

Table 1. Comparison of different types of VSI in terms of design, implementation & complexity.

Characteristic	Cascaded H-Bridge VSI	NP-Diode Clamped VSI	Flying Capacitor VSI	2L-VSI
Design & implementation complexity	High	Low	Medium	Low
Specific Requirements	Separate DC sources	Clamping diodes	Additional capacitors	IGBTs/MOSFETs
Control Concerns	Power Sharing	Voltage balancing	Voltage Setup	Voltage/current regulation
Modularity	High	Low	High	Low
Fault tolerance ability	Easy	Difficult	Easy	Easy
Reliability	Medium	Medium	Medium-High	High
Converter Complexity	Medium	Medium	Low-Medium	High
Controller Complexity	Medium-High	Medium-High	Medium-High	Medium
Power Quality	Good	Good	Good	Medium
Operational Power (MW)	3–6	3–7	3–6	3
Switching devices	MV-IGBT, IGCT	MV-IGBT, IGCT	MV-IGBT, IGCT	LV-IGBT

### 3. Characteristics of Control Systems

There are several parameters and characteristics through which a particular control system is identified. Mainly, there are two characteristics of a control system are found i.e., analog or digital control systems. Both are having some advantages and disadvantages, described as follows:

### 3.1. Analog Control System

The control systems in which the input and output are designed and analyzed by continuous time analysis or Laplace transform (in s-domain) using state-space formulations. In analog control systems, the representation of the time domain variable is assumed to have infinite precision. Hence, the equations of state space model are differential equations. These systems can be designed without using a computer, microcontrollers or a programmable logic control (PLC). Implementation of analog signals is generally done by using Op-amps, capacitors etc. Robustness against crash or breakdown, having a wide dynamic range, analytical composition accessibility and continuous processing indicate numerous advantages of the analog control systems. However, slow processing speed, interference, complicated implementation in comparative logic, intelligent control systems, neural networks and MIMO are several disadvantages of analog control systems.

### 3.2. Digital Control System

In digital control systems, modeling, designing, implementation and analysis is carried out in discrete-time or z-transformation domain. In digital control systems, as the name depicts that digital signals are analyzed. Therefore, time is sampled and quantized for state space equations. Additionally, as a digital computer has finite precision, extra attention is needed to ensure that error in coefficients, i.e., A/D conversion, D/A conversion etc. are not producing any disturbances or inadequate effects. In a digital controller, the output is a weighted sum of current as well as previous input and output samples, therefore, its implementation requires the storage of relevant values in a digital controller.

Mostly, a digital controller is implemented via a computer, so, found most economical to control the plants. Moreover, it is relatively easier to constitute and reconstitute through software. Likewise, programs can be leveled to the confines of storage without any additional cost. Correspondingly, digital controllers are compliant with constraints of the program can be changed. Furthermore, the digital controllers are less responsive to the changes in environmental conditions, unlike the analog controllers. Flexibility, swift expansion, uncomplicated implementation in comparative logic, intelligent systems and MIMO, high accuracy as well as robustness against interference are several advantages of these systems. Though, low processing speed, low dynamic range and non-user-friendly interface are the several drawbacks of the digital control systems. The digital controllers are implemented with various technologies which are classified into three categories expressed as follows:

1. Microcontroller Based implementation (MC) [49–51]
2. Digital Signal processing-based implementation (DSP) [52–54]
3. Field programmable gate array-based implementation (FPGA) [55–57]

In reliable scientific research, generally, DSP is used. Fixed point arithmetic and floating-point algorithms are mostly used in implementing the digital control technique by DSP. A traditional slow microprocessor is used normally in slow applications. However, an FPGA is found adequate in fast controllers, due to its abilities of bug fixing and to be reprogrammed in complex structures.

A general structure of a closed loop grid connected digital control system, with an inner current loop and an outer voltage loop, is depicted in Figure 10. In this figure, a voltage source inverter with an output filter is considered. An AC bus is connected to point of common coupling, PCC. Moreover, coordinates transformation from abc to dq is achieved by a phase angle, PH. However, PLL represents the phase locked loop. The symbols  $S_1$ ,  $S_2$ ,  $S_3$ ,  $S'_1$ ,  $S'_2$  and  $S'_3$  represents the switches, responsible for positive and negative sequences of the inverter output.

The  $v_{dref}$ . and  $v_{qref}$ . represents the reference voltages in dq frame. SVPWM shows the space vector pulse width modulation technique for generating drive signals for a voltage source inverter.

The voltage across capacitors,  $u_c$  and current across inductors,  $i_L$  are measured and transformed into a synchronized dq reference frame. The input voltage is computed in the dq frame on the basis of  $v_{ref}$ . in the three-phase reference frame. The computed data is then transformed from rotating dq to abc reference frame. Afterward, the PWM technique would be selected accordingly.



current injected into the loads is assumed as the reference direction. The mathematical representation of a steady-state model is expressed as following:

$$\begin{cases} u_{bd} = \omega L i_{sq} + u_{sd} \\ u_{bq} = -\omega L i_{sd} + u_{sq} \end{cases} \quad (1)$$

In Equation (1), the terms  $u_{bd}$  and  $u_{bq}$  represents the voltages in dq frame under balanced network conditions. Likewise,  $k_p$  and  $k_i$  represents the proportional and integrated controllers and the equation by using aforementioned coefficients represents a PI controller. Correspondingly,  $u_{sd}$  and  $u_{sq}$  represents the bus voltages in dq axis. However,  $i_{sd}$  and  $i_{sq}$  represents the active and reactive current respectively. Commonly, the  $d$ -axis is fixed to the voltage source space vector, i.e., the amplitude of the desired ac voltage space vector is kept constant and the value of  $u_{sq} = 0$ . Then Equation (1) can be simplified as:

$$\begin{cases} u_{bd} = \omega L i_{sq} + u_{sd} \\ u_{bq} = -\omega L i_{sd} \end{cases} \quad (2)$$

According to Equation (2), the control structure of the inverter station is shown in Figure 11, where a PI controller is employed in the ac voltage control [60]. Moreover,  $u_{sref.}$  is the reference voltage which can be set accordingly for the desirable amplitude of AC bus voltage.

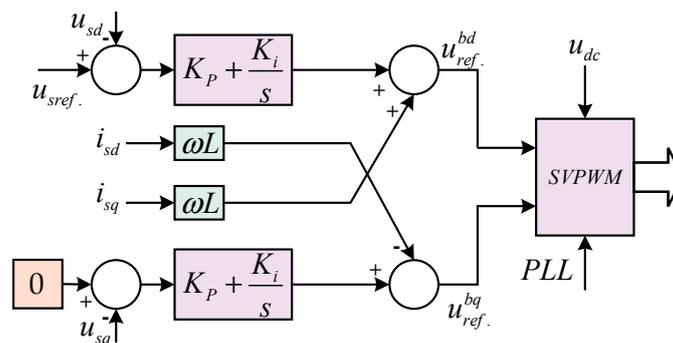


Figure 11. The decoupling control strategy in dq reference frame.

### 6. Time Delay Sampling Scheme for VSI

Time sampling for digital controllers is done by using a discrete time-domain analysis, i.e., z-domain. Two fundamental advantages of using z-domain analysis over s-domain (continuous time domain) analysis for designing a current controller are: First the control implementation is achieved on a computer-based system, i.e., the control calculation, sampling measurements and PWM signals sequence are updated in discrete time steps. Although, this sample and hold feature is a characteristic of a control system and effects its dynamics as per the referred sampling frequency. Secondly, the multiple time delays can be modeled by using a backshift operator, which affords no simplifications in linear control design, unlike continuous time domain, where the multiple time delays were sampled using an exponential term, which is approximated generally by applying Taylor-series expansion. The sampling effect is a most critical requirement to handle model uncertainties, issues in power supplies and relative disturbances. Therefore, in order to deal with aforementioned issues, zero order hold, ZOH should be incorporated in the control system. In ZOH, a pole or a zero is added into the existed controller through the compensator. The fundamental advantage of this technique is its uncomplicated structure to be implemented on a system, though, it only affects a limited share of the overall delay.

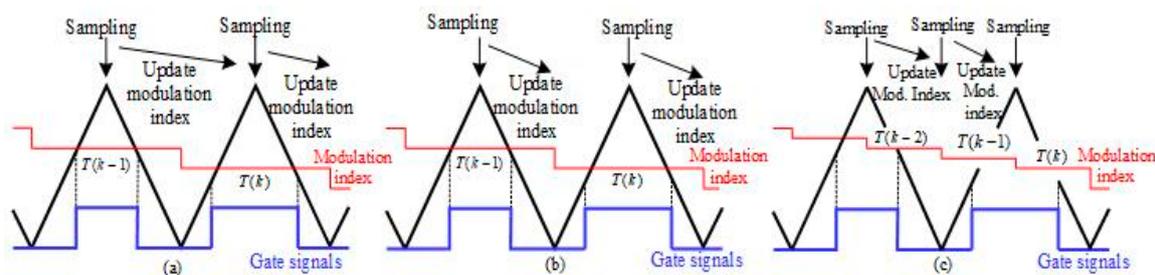
There are two basic sampling routines generally employed in the digital control systems, i.e., single updated sampling and double updated sampling [61]. A single-update sampling method comprises of the measurement samplings, in which calculated modulation indexes are updated once in every

switching period. Whereas, a double-update sampling concept conferred to a PWM concept in which the measurement sampling and therefore, the calculated modulation index are updated twice in every switching period [61]. The detailed single-update and double-update sampling are shown in Figure 12, where,  $T(k)$  represents the switching period of the present time slot. However,  $T(k - 1)$  and  $T(k - 2)$  shows the switching period of the former time slots.

A single-update PWM-technique with sampling at the beginning of a switching period is depicted in Figure 12a. In this technique, the modulation index is updated once in beginning of a switching period. A time domain of one sampling time is introduced in the control loops. This effect is modeled with a backshift operator while taking discrete time domain into the account.

Figure 12b shows another scheme of a single-update PWM sampling in which the modulation index is updated in middle of a switching period. Therefore, the time delay due to sampling and updating routine is the mean value of the two converter voltage reference values, i.e., actual and former control cycles. Therefore, the transfer function of a single-update PWM technique with sampling in middle of a switching period is determined.

In the double-update sampling concept, sampling and updating occurs twice in each sampling period. In this technique, the modulation index is updated on the basis of former control cycle's measurements. According to this behavior, the time-delay is one control cycle. The pattern of a double-update sampling is presented in Figure 12c.



**Figure 12.** Time delay model of a VSI (a) single-update time delay model (sampling at beginning) (b) single-update time delay model (sampling at middle) (c) double-update time delay model for a VSI.

## 7. Output Filters for Inverters

The harmonics reduction is the foremost priority of the researchers while designing a power electronics or an electrical system. Therefore, an output filter is used for this purpose. An output filter uses the controlled phenomenon of switching the semiconductor devices for harmonics reduction. There are numerous topologies of such filters introduced in the literature by combining the inductor (L) and capacitor (C) i.e., L, LC and LCL filters unified with the inverters to their output.

### 7.1. L-Filter

In high switching frequency inverters, the first order L-filter is considered as the most suitable filter. However, inductance decreases the dynamics of the whole system.

### 7.2. LC-Filter

An LC filter is a second-order filter having substantially sophisticated damping behavior as compared to an L-filter. This filter topology is relatively easier to design and it is a compromise between the values of inductance and capacitance. The cut-off frequency needs the relatively higher value of inductance whereas the voltage quality can be improved through the higher value of capacitance. The value of resonant frequency is dependent on the impedance of the grid when the system is connected to the grid supply. An LC-filter is mostly preferred in standalone mode. The three-phase

two-level and three-phase four legs voltage source inverters with an integrated LC filter are shown in Figures 7 and 8 respectively.

7.3. LCL-Filter

An LCL filter is a third order filter, mostly used for the grid-tied inverters. The lower frequency is preferable in presence of aforementioned filters. This filter supports the comparatively healthier decoupling between the filter and the grid impedance. This filter should be precisely designed by taking into consideration the parameters of the inverters. Otherwise even the smaller values of inductance can bring resonance and unstable states into the system. However, the smaller inductance can provide optimized current ripple diminishing values. A three-phase VSI with an LCL filter is shown in Figure 13. Where,  $V_{th}$  and  $Z_{th}$  represents the Thevenin voltage and Thevenin impedance respectively. However, the complexity of the control system inflated significantly and the dynamic performance of the inverter can perhaps be affected when relatively complex filter structures are employed. Thus, these topologies are most suitable for high power applications, which employ low switching frequencies. However, Figures 14 and 15 show the one-leg block diagram of a single-phase and three-phase grid-connected systems, respectively. Where,  $K_{pwm}$  represents the pulse width modulation characteristic of the system, whereas,  $u_g, u_i, u_c, L_g, L_i, i_i$  and  $i_g$  represents the grid side voltage, inverter side voltage, voltage across capacitor, grid side inductance, inverter side inductance, inverter side current and grid side current respectively.

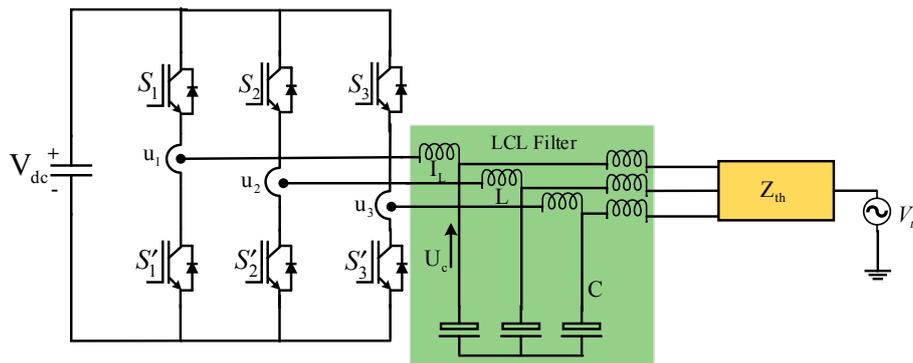


Figure 13. A Three-phase voltage source inverter in grid-connected mode.

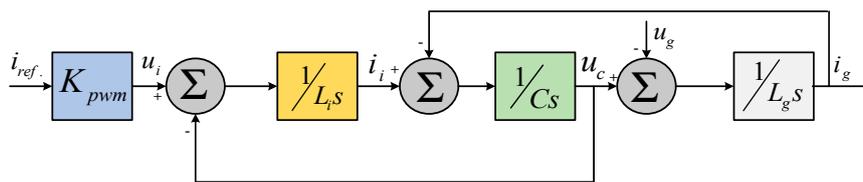


Figure 14. One-leg block diagram of a single-phase grid-connected system.

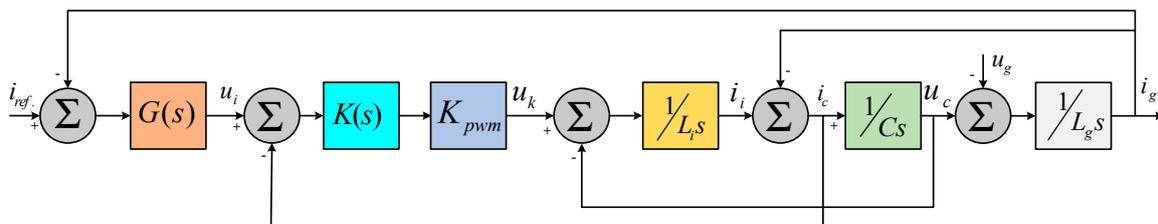


Figure 15. One-leg block diagram of a dual-loop current control strategy for VSI.



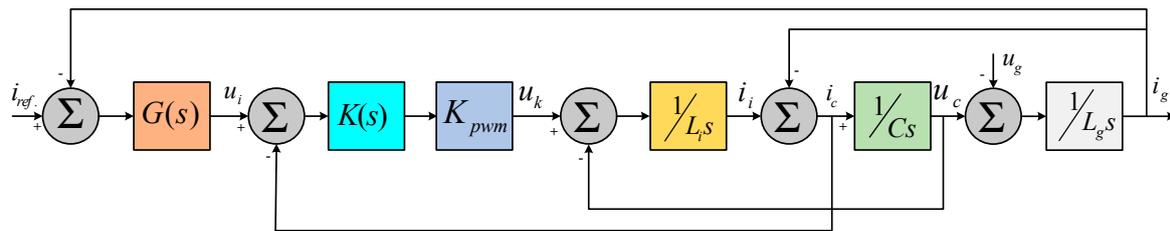


Figure 17. One-leg block diagram of an active damping control strategy for a grid-connected VSI.

## 9. Grid Synchronization Techniques

The grid voltage must be synchronized with the injected current in a utility network for a significant output. In synchronization algorithm, phase of the grid voltage vector is considered and control variables i.e., grid voltages and grid currents are synchronized by using it. Various methods are introduced in literature for extracting the phase angle [68]. Some commonly used techniques found in credible research articles are discussed as:

### 9.1. Zero-Crossing Technique

The simplest method to implement is Zero-Crossing method. However, it is not considered on a larger scale due to poor performances reported in the literature. Especially, during voltage variations, ample values of harmonics and notches are observed.

### 9.2. Filtering of Grid Voltages

The grid voltages can be filtered in the  $dq$  frame as well as in the  $\alpha\beta$  reference frame. The performance of zero-crossing method is improved by voltage filtering [68]. However, it is a complicated process to extract the phase angle out of utility voltage, especially during a fault condition. This method uses the arctangent function to realize the phase angle. Generally, a delay is observed in processing a signal while using the filtering method. Therefore, designing of the filter must be considered critically.

### 9.3. Phase Locked Loop Technique

The phase locked loop, PLL technique is considered as the state-of-the-art method to obtain the phase angle of the grid voltages. The PLL is implemented in dq-synchronous reference frame. In this case, the coordinates transformation from abc to dq is preferred and reference voltage,  $\hat{u}_d$  would be set to zero for realizing the lock. A general schematic of PLL technique is depicted in Figure 18. A PI regulator is generally used to control the reference variable. Afterward, the grid frequency is integrated in the system and utility voltage angle is acquired after passing through a voltage-controlled oscillator, VCO. This voltage angle is then fed into the  $\alpha\beta$  to dq transformation module for transforming into the synchronous reference frame.

This technique is found the most suitable for rejecting notches, grid harmonics and other disturbances. However, additional improvements are needed to handle the unsymmetrical voltage faults. Especially, filtering techniques to filter the negative sequence should be proposed in case of unsymmetrical voltage faults, as second-order harmonics are propagated by the PLL system and reflected in the obtained phase angle. Moreover, it should be assured to estimate the phase angle of the positive sequence of the grid voltages during unbalanced grid voltages [68].

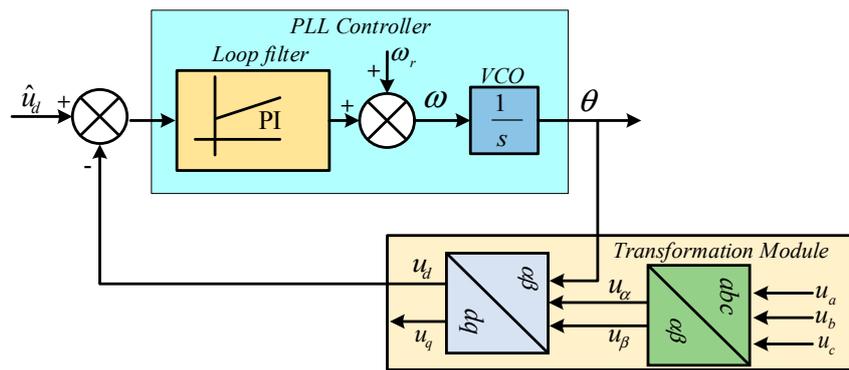


Figure 18. General schematic of a three-phase PLL technique.

## 10. Modulation Schemes

In power electronics converters, the major problem is the reduction in harmonics. PWM control techniques provide the most suitable solution for harmonics reduction. A sinusoidal output having controlled values of frequency and magnitude is the core purpose for using these PWM techniques. Primarily, PWM techniques are classified into three major categories i.e., Triangular Comparison-based PWM (TC-PWM), Space Vector-based PWM (SV-PWM) and Voltage look-up table-based PWM (VLUT-PWM).

### 10.1. Triangular Comparison Based PWM

In Triangular Comparison based PWM (TC-PWM) techniques, PWM waves are produced by the combination of an ordinary triangular carrier and a fundamental modulating reference signal. The triangular carrier signal has relatively very higher frequency than that of a fundamental modulating reference signal. The magnitude and frequency of the fundamental modulating reference signal control the magnitude and frequency of the central module in the grid side. PWM and Synchronous PWM (SPWM) are the core techniques to be mentioned in TC-PWM [69].

### 10.2. Space Vector Based PWM

In SVPWM techniques, the revolving reference vectors provide the reference signals. The magnitude and frequency of central module in grid side are controlled by the frequency and magnitude of the revolving reference vectors respectively. This technique was first introduced to generate vector based PWM in the three-phase inverters. However, nowadays it is expanded to various other newly introduced inverters. SV-PWM is considered to be the more advanced technique for PWM generation for getting qualified sinusoidal output with low THD values [69].

### 10.3. Voltage Look-Up Table-Based PWM

In VLUT-PWM, a new method is introduced to obtain the voltage reference based on the current reference for an inverter. The major advantage of this technique is its compatibility and simplicity with the load conditions. The switching frequency in this technique is usually taken significantly lower as compared to various other presented techniques [52].

## 11. Control Techniques

Connecting the grid to the distributed generation system plays a key role and if bit negligence is shown in implementing this procedure, a number of problems can arise i.e., the grid uncertainty and disturbance, so in order to overcome this situation, a suitable controller must be designed for it. In this section, the most appropriate control techniques are described according to their applications. Various single loop and multiloop control systems are discussed in the literature for power droop

control, voltage and current control. In which inner loop is for current regulation and outer loop is for voltage regulation [13,70,71]. In Figure 19, the categorization of classical and advanced control techniques is depicted clearly.

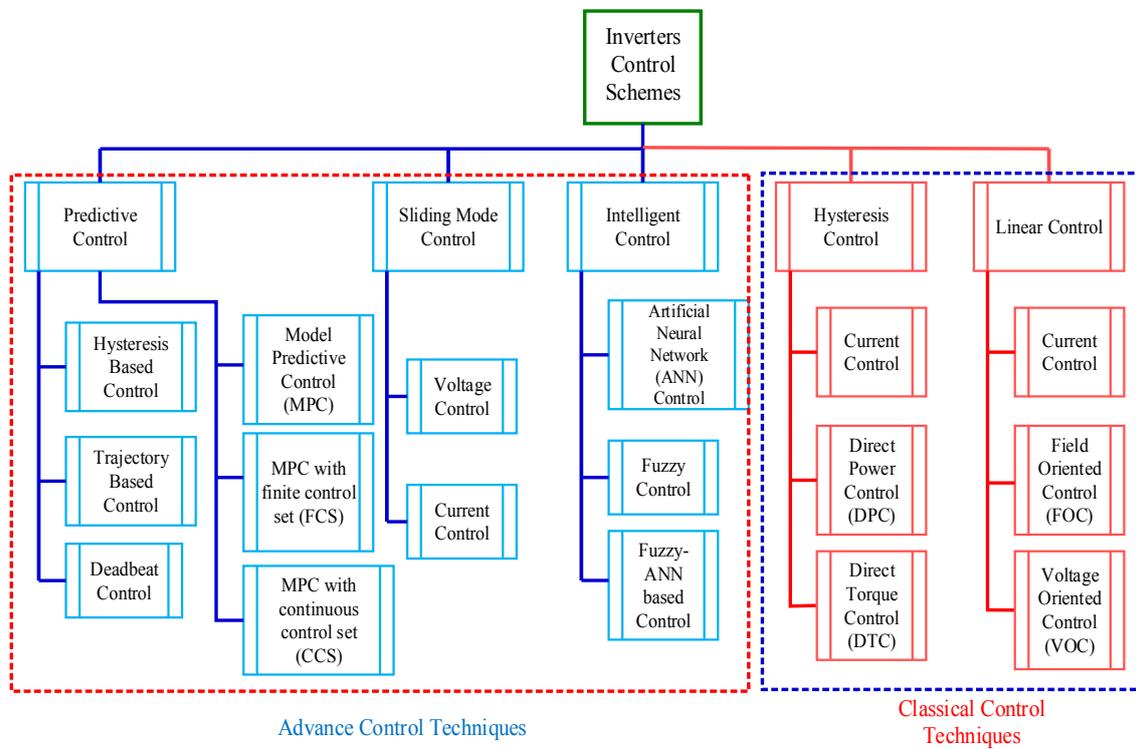


Figure 19. Classification of control techniques for VSIs.

### 11.1. Classical Control Techniques

The classical controllers include the category of controllers for adding or subtracting a proportion and adjusting the system accordingly. These controllers involve proportional (P), proportional integration (PI), proportional integral derivative (PID) and proportional derivative (PD) controllers. These controllers are considered as the most fundamental controllers in the industry for controlling linear systems and considered as the base of control theory. Lot of work in literature is being done on these controllers [49–52,72–78]. The fundamental benefits of implementing these controllers are their ability to tune themselves according to the requirement of the plant and their simple structure. Moreover, they are the most commonly used controllers on commercial levels, so easily available. However, their tracking ability, response time and ability to handle stable error are relatively lower as compared to modern state-of-the-art controller. The schematic of a digital PI controller for controlling a three-phase VSI with an LC filter in stand-alone mode is shown in Figure 20. In Figure 20,  $i_{af}$ ,  $i_{bf}$  and  $i_{cf}$  represents the filter current across phase a, b and c respectively. Likewise,  $v_a$ ,  $v_b$  and  $v_c$  characterizes the voltage across phase a, b and c respectively. Likewise,  $i_d$  and  $i_q$  represents the current across the d and q axis respectively. Moreover,  $S_a$ ,  $S_b$  and  $S_c$  represents the switching commands across phase a, b and c respectively. Correspondingly,  $V_{ref}^d$  and  $V_{ref}^q$  symbolizes the reference voltages along d and q axis respectively.



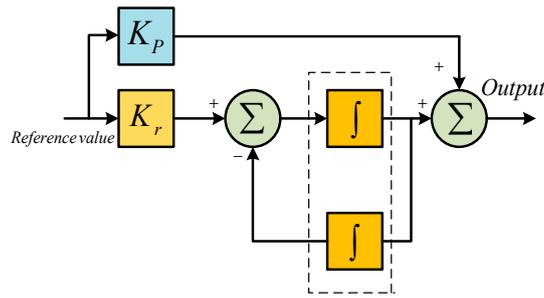


Figure 22. General structure of a PR Controller.

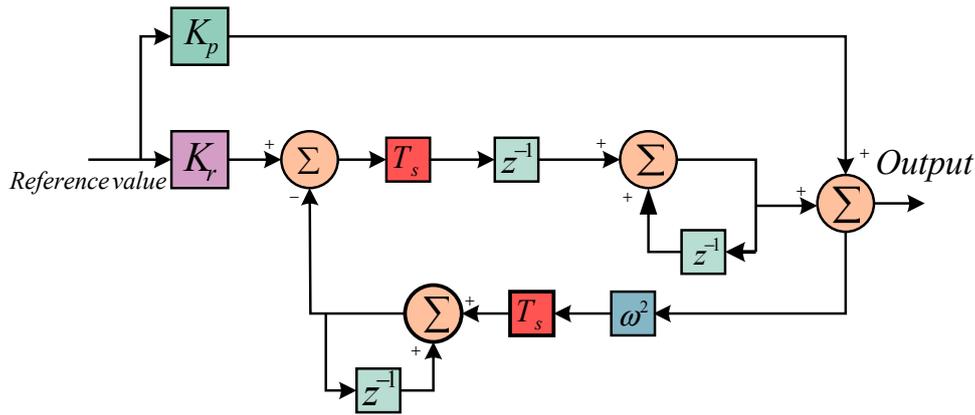


Figure 23. Structure of a discrete PR Controller.

11.3. LQG Control Technique

The integration of Kalman filter with an LQR controller gives rise to an LQG controller. In this technique, Kalman Filter, as well as an LQG controller, can be designed independently of each other. This control scheme is valid for both linear time-invariant systems as well as for linear time-varying systems. LQG control technique facilitates the designing of a linear feedback controller for an uncertain nonlinear control system [79–81]. An LQG control structure with a Kalman estimator is shown in Figure 24. Where,  $u_e$  represents the known input and  $y_c$  is the estimated noise/disturbance. The Kalman estimator provides the optimal solution to the continuous or discrete estimation problems.

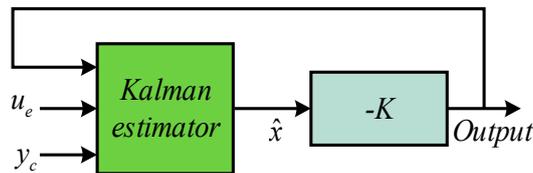


Figure 24. Structure of an LQG controller.

11.3.1. Linear Quadratic Regulator

The linear quadratic regulator (LQR) technique is found optimal for steady as well as transient states [82–84]. As the name depicts, this control technique is a combination of linear and quadratic functions, where the dynamics of the system are described by a set of linear equations and the cost of the system is a quadratic function. The cost function parameters are considered critically while designing the controller. LQR algorithm is an automatic approach for finding a suitable state-feedback controller. Pole placement with state feedback controller provides the system with a high degree of freedom and makes it simpler to implement. This method is characteristically steady and it can be

employed even if some of the system parameters are unknown. However, exertion in finding the exact weighting factors limits the applications of LQR control scheme. Moreover, it has a discrepancy of tracking accuracy during load changes [83–85].

### 11.3.2. Linear Quadratic Integrator

In linear quadratic integrator (LQI) scheme, cost minimization is considered critically. This technique is implemented for nullifying the steady-state error between actual grid voltage and reference grid voltage during load variations [82]. An integral term used with LQ control is for minimizing the tracking error produced by uncertain disturbances in instantaneous reference voltage. Optimal gains for providing adequate tracking with zero steady-state error are relatively simpler to attain by using this technique. The rapid dynamic response, accurate tracking ability and relatively simpler designing procedure provide this technique a benefit over other techniques. However, complications in extracting the model and phase shift in voltage tracking even in normal operative condition are the major drawbacks of this scheme.

### 11.4. Hysteresis Control Technique

Hysteresis control is considered as a nonlinear method [86–93]. The hysteresis controllers are used to track the error between the referred and measured currents. Therefore, the gating signals are generated on the basis of this reference tracking. Hysteresis bandwidth is adjusted for error removal in reference tracking. This is an uncomplicated concept and has been used since analog control platforms were intensively used. This technique does not require a modulator; therefore, the switching frequency of an inverter is dependent on the hysteresis bandwidth operating conditions and filter parameters [94]. The major drawback of hysteresis controller is its uncontrolled switching frequency; however, researchers are working on improving this controller and several works are presented and several techniques are proposed in the literature. Main advances in this technique are direct torque control (DTC) [87,88,95,96] and direct power control (DPC) [97–99]. In DPC, active and reactive powers are directly controlled, however, in DTC torque and flux of the system are controlled. Error signals are produced by hysteresis controllers and drive signals are generated by the look-up according to the magnitude of the error signals. Hysteresis controllers require very high frequency for constraining the variables in hysteresis band limits, whenever implemented on a digital platform as shown in Figure 25. Moreover, switching losses are very high in this type of controllers. So, Hysteresis controllers are found inappropriate for high power applications.

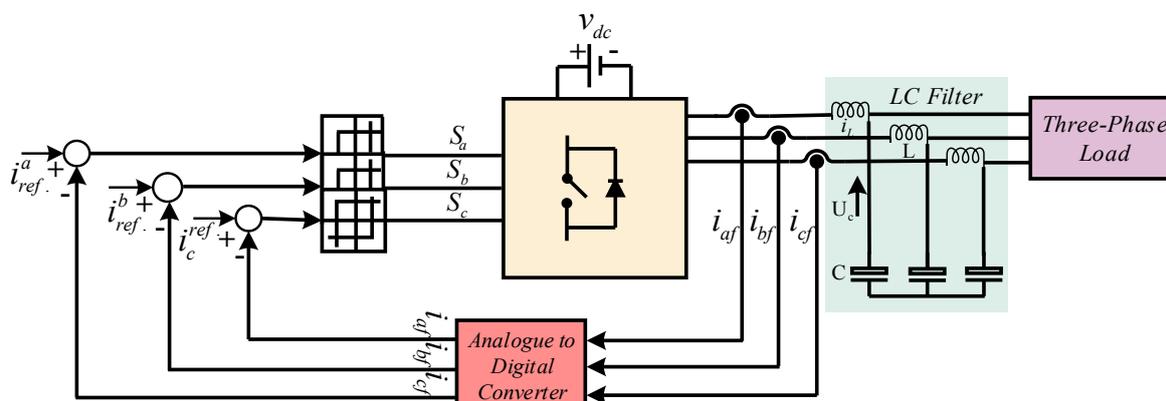


Figure 25. A Hysteresis control technique for VSI.

### 11.5. Sliding Mode Control

The sliding mode control is considered to be an advanced power control technique for the power converters. It fits into the family of adaptive control and variable structure control [100–104].

Sliding mode control is a non-linear technique, whereas it can be instigated to both non-linear as well as linear systems [100]. In Figure 26, a sliding mode control along with SVM/PWM is presented. Where,  $\beta_v$  represents the gain,  $\lambda$  is a strictly positive constant and  $\phi$  is a trade-off between the tracking error and smoothing of the control discontinuity. The sliding controller produces the voltage references in a converter for generating the drive signals. A predefined trajectory is executed and the control variable is forced to slide along it [102–104]. The robust and stable response is achieved even in the system parameters variation or load disturbances by implementing sliding mode control technique. This controller is more robust and capable of removing the stable error as compared to the classical controllers. However, some drawbacks in implementing a sliding mode control are difficulty in finding a suitable sliding surface and limitation of sampling rate that degrades the performance of SMC will be degraded. Whenever tracking a variable reference, the chattering phenomenon is another drawback of SMC technique. As a result, overall system efficacy is reduced [105,106].

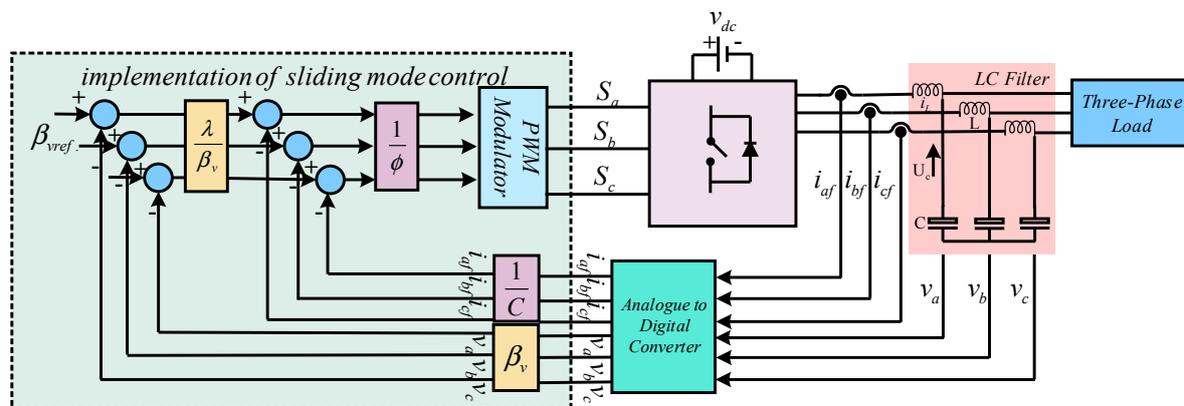


Figure 26. A Sliding mode control technique on a VSI.

### 11.6. Partial Feedback Controllers

There are several techniques presented for conversion of non-linear systems to linear systems for their uncomplicated computation. Partial feedback controllers are one of the most effective and forthright techniques for transforming the non-linear systems into the linear ones. By this technique, a system can be converted either partially or fully into a linear system, depends on the system constraints. Linearity in a system is attained by the cancellation of the nonlinearities inside the system. So, these systems can be controlled by using the linear controllers whenever a non-linear system is fully transformed into a linear system i.e., exact feedback linearization method. However, if it is partially converted into a linear system then it is known to be partial feedback linearization. PFL controller is implemented in [104,106–109]. In PFL, it is difficult to ensure the stability of complicated renewable energy system applications. However, an independent subsystem can be obtained from PFL for constraining the extensive use of this method. Moreover, in order to deal with these problems, exact feedback linearization (EFL) is a forthright and model-based technique for scheming nonlinear control techniques. EFL receipts the built-in nonlinearity characteristic of the system under deliberation and consents the conversion of a nonlinear structure into a linear one, algebraically. EFL removes nonlinearities of a system through nonlinear feedback, as a result, the transformed system is not reliant on an operating point.

### 11.7. Repetitive Control

The plug-in scheme (PIS) and internal model (IM) principle are the basic concepts of repetitive control (RC). RC uses an IMP which is in correspondence to the model of a periodic signal. In order to derive this model, trigonometric Fourier series expansion is used. If the model of reference is fed into the closed loop path, optimal reference tracking can be obtained. Moreover, it is found robust against

disturbances and has the ability to reject them. RC mostly deals with periodic signals. Closed loop behavior of the system and Magnitude response of the IM are the core factors used for analyzing the performance of the repetitive controller in case of frequency variation or any other uncertainty in the system. Both these factors indicate the performance sagging in case of variation or uncertainty in the reference signal. In presence of a periodic disturbance, RC intends to attain zero tracking error when a periodic or a constant command is referred to it. RC has an ability to locate an error, a time-period before and fine-tunes the next command according to the feedback control system for eliminating the observed error. However, it lacks the ability to handle physical noise. For this purpose, an LPF can be used. Kalman’s filtering approach is also noticeable to remove this noise [27,110–113]. The general structure of a repetitive controller is shown in Figure 27.

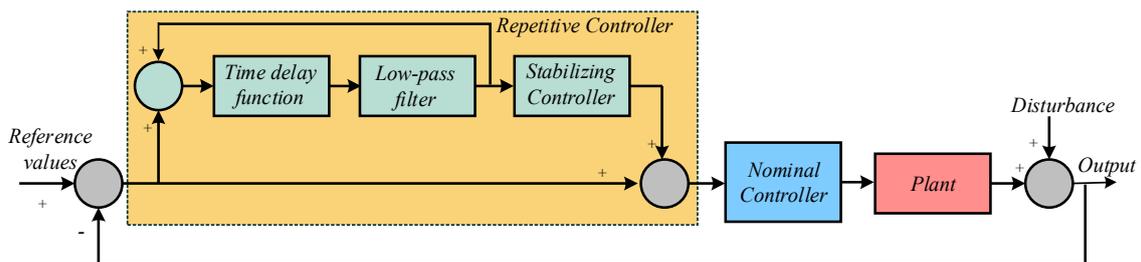


Figure 27. Block diagram of Repetitive control algorithm.

### 11.7.1. Fuzzy Control

This control technique belongs to the family of intelligent control systems. The PI controller is replaced by a fuzzy logic controller in this technique as shown in Figure 28. Where,  $v_{fz}$  is the fuzzified output voltage. However, its block diagram is shown in Figure 29. In a fuzzy controller, the tracking error of load current and its derivative are given as the input. This controller design is dependent on the awareness, knowledge, skills and experience of the converter designer in terms of functions involvement. Due to non-linear nature of the power converters, the system can be stabilized in case of parameters variation even if the exact model of the converter is unknown. Fuzzy logic controllers are also categorized as non-linear controllers and probably the best controllers amongst the repetitive controllers [113–116]. However, strong assumptions and adequate experience are required in fuzzification of this controller. As it is dependent on the system input and draw conclusions according to the set of rules assigned to them during the process of their modeling and designing.

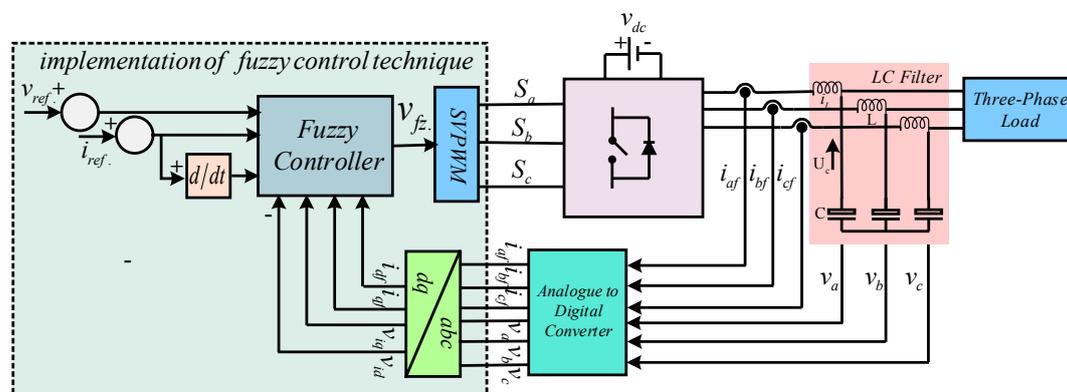


Figure 28. A Fuzzy control algorithm topology on a VSI.

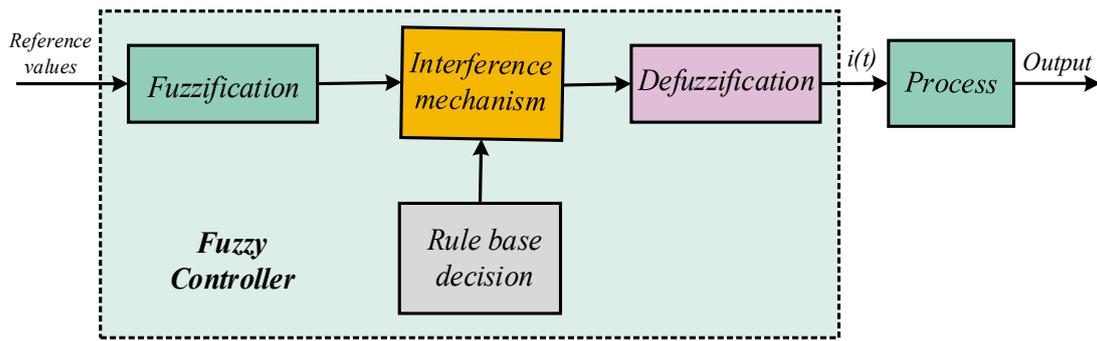


Figure 29. Block diagram of Fuzzy control algorithm.

### 11.7.2. Artificial Neural Network Control

The Artificial neural network (ANN) controllers are the fundamental form of the controllers based on the human-thinking mode. It consists of a number of artificial neurons to behave as a biological human brain. The reference tracking error signals are given through a suitable gain or a scaling factor (S) as input to the ANN for generating the switching signals into the power converters. This approach is used for achieving the constant switching operation in power converters. ANN can be used in both online as well offline modes while operating it on system control. It has high tolerance level to faults because of its ability to estimate the function mapping. Its topology is shown in Figure 30.

Fuzzy and ANN can be combined to achieve an optimal control performance in a power converter [113–115]. ANN does not need a converter model for its operation, however, the operational behavior of a power converter should be precisely known to the designer/operator while designing the ANN control system.

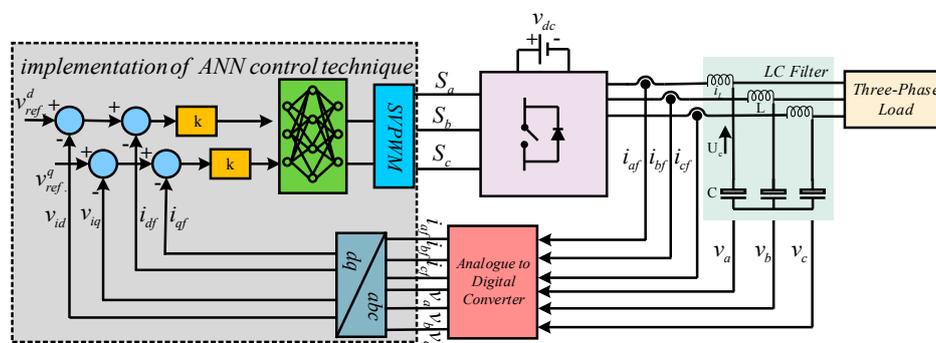


Figure 30. Schematic of Artificial Neural Network control for VSIs.

### 11.8. Robust Controllers

In robust control theory, a control system vigorous against uncertainties and disturbances is offered. The basic aim is to attain the stability in case of inadequate modeling. All the descriptions, criteria and limitations should be appropriately defined in order to get robust control. This controller guarantees the stability and high performance of closed-loop system even in multivariable systems [117].

#### 11.8.1. H-Infinity Controllers

The expression  $H_\infty$  control originates from the term mathematical space on which the optimization takes place:  $H_\infty$  is considered as a space of matrix-valued functions that are investigative and confined in the open right-half of the complex plane. In this type of control system, first of all, the control problem is formulated and then mathematical optimization is implemented i.e., selection of the best element according to criterion from the set of obtainable alternatives. H-infinity control

techniques are generally pertinent for the multivariable systems. The impact of a perturbation can be reduced by using H-infinity control techniques in a closed loop system subject to the problem formulation. The impact can be measured either in terms of performance or stabilization of the system. However, modeling of the system should be well-defined for implementation of these control techniques. Moreover, H-infinity control techniques have another discrepancy of high computational complications. In case of non-linear systems limitations, the control system cannot handle them well and response time also increases [118]. However, these controllers are implemented and well defined in [111,112,119].

### 11.8.2. $\mu$ -Synthesis Controllers

Mu-synthesis is based on the multivariable feedback control technique, which is used to handle the structured as well as unstructured disturbances in the system. Where  $\mu$  mentions the singular value that is reciprocal of the multivariable stability margin. The basic purpose is to mechanize the synthesis of multivariable feedback controllers that are insensitive to uncertainties of the plant and be able to attain the anticipated performance objectives. This method is well described in [120,121].

### 11.9. Adaptive Controllers

An adaptive controller is designed to have the ability of self-tuning, i.e., to regulate itself spontaneously according to variations in the system parameters. It does not require initial conditions, system parameters or limitations for its implementation due to its ability to modify the control law according to system requirements. Recursive least squares and Gradient descent are two most commonly known technique for parameters estimation in adaptive controllers. The structure of a typical adaptive controller is shown in Figure 31. In the literature, some credible research articles and state-of-the-art techniques for adaptive controllers are found in [14,37,53,55,113,122–125]. These controllers are applicable for both dynamic as well as static processes. However, the complicated computational process leads to exertion in its implementation.

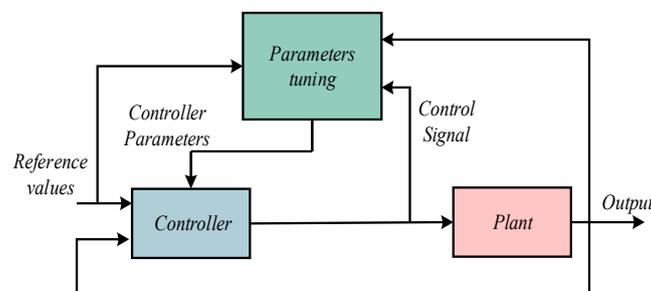


Figure 31. Block diagram of Adaptive control algorithm.

### 11.10. Predictive Controllers

Predictive controllers are commenced as a propitious control technique for electronics inverters. The system model is considered critically and then imminent behavior of the control variables is predicted conferring to the specified criterion. It is an uncomplicated technique and can handle multivariable systems efficiently. Moreover, it can handle the system with several limitations or non-linearities. It is generally preferred due to its prompt static as well as dynamic response and ability to handle stable errors. However, its computational analysis is complex as compared to classical controllers. It is further categorized into Deadbeat control and Model Predictive control. It can refer to literature [105,125–127] for predictive controllers. A comparison of predictive control techniques on basis of their pros. and cons. is described in Table 2.

11.10.1. Deadbeat Control

Deadbeat control technique is the most authentic, competent and attractive technique in terms of low THD value, frequency as well as rapid transient response. Differential equations are derived and discretized in this type of control system for controlling the dynamic behavior of the system. The control signal is predicted for the new sampling period for attaining the reference value. Its effective dynamic performance and high bandwidth simplify the current control for this type of controller. Error compensation is a specialty of a deadbeat controller. However, its major discrepancy is its sensitivity for network parameters and accurate mathematical filter modeling [13,54,56,128–135]. Its topology is shown in Figure 32, where a disturbance observer, a state estimator and a digital deadbeat controller are used to control the voltage and current of a VSI. The coefficient  $\hat{d}$  represents the output of disturbance observer comprises of current and voltage. However,  $\hat{v}_d$  and  $\hat{v}_q$  represents the controlled voltage across  $d$ -axis and  $q$ -axis respectively.

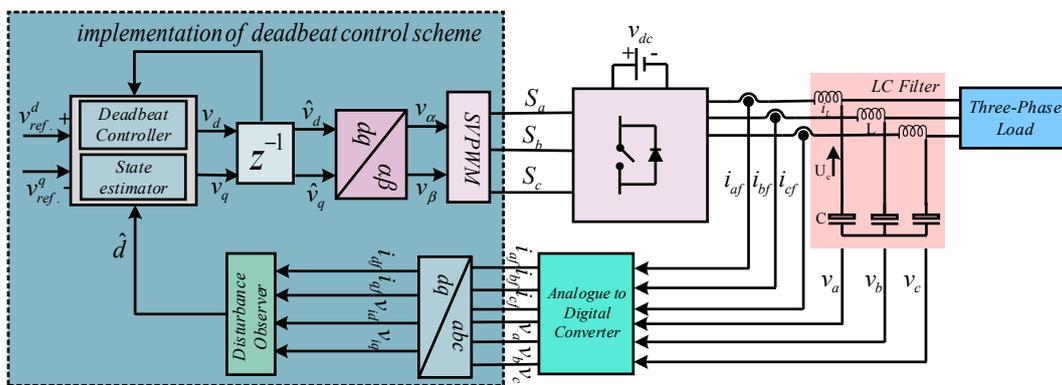


Figure 32. Deadbeat control topology for VSIs.

11.10.2. Model Predictive Control

As the name depicts, a model of the system is used to predict the behavior of the system in model predictive control (MPC) technique. A cost function criterion is defined in this type of control system, which can be minimized for optimal control actions. The controller adapts the optimal switching states according to the cost function criterion. Forecast error can be lessened for current tracking implementing. Moreover, system limitations and non-linearities, as well as multiple inputs and output systems, are handled well by MPC. Control actions of the present state are considered in order to predict the control actions of the system in the next state. Like deadbeat control, it is also found sensitive to system parameter variations [136–147]. The topology for implementation of MPC on VSI is shown in Figure 33, whereas, its control schematic is depicted in Figure 34.

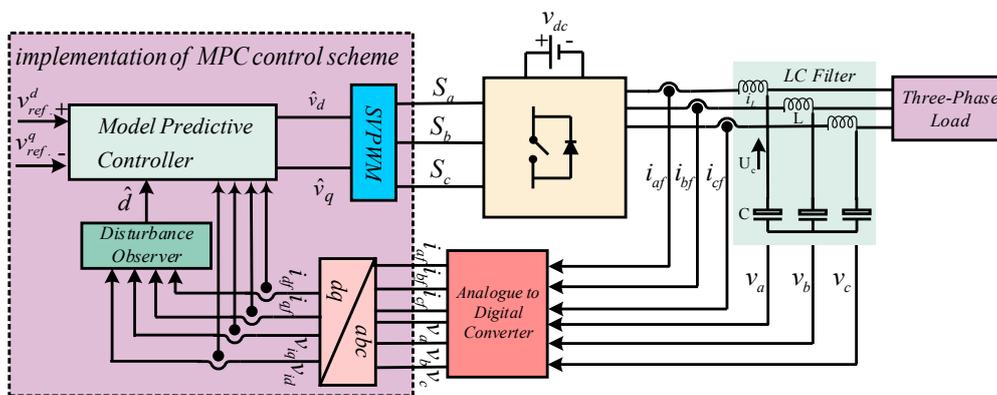


Figure 33. Model Predictive Control topology for VSIs.

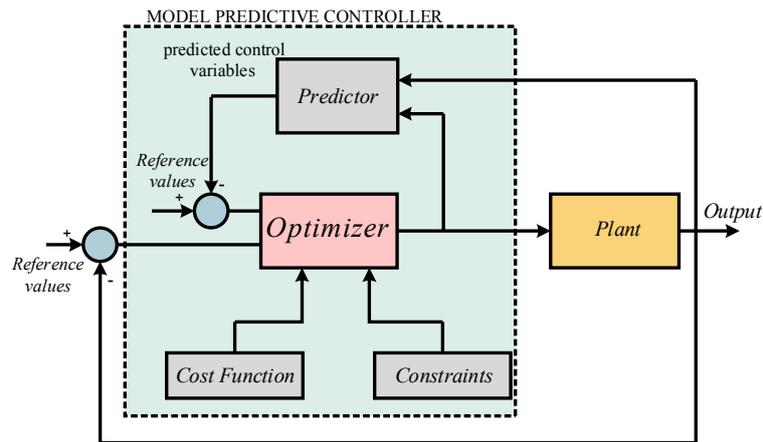


Figure 34. Block Diagram of Model Predictive Control algorithm.

### 11.11. Iterative Learning Scheme

Iterative Learning Scheme (ILS) is a complicated but authentic technique for attaining zero tracking error. In this scheme, each control command is executed and the system is examined and then adjusted accordingly before each repetition. Highly accurate modeling of the system is essential for the implementation of ILS; therefore, its designing technique is relatively more complicated than other schemes. ILS is capable of removing the tracking error caused by the periodic disturbances. The next cycle is predicted by considering the learning gain, system adjustment in z-transform, tracking error at each repetition, control function of the designed controller and the error function between two consecutive iterations.

## 12. Comparative Analysis and Future Research Goals

VSI are specially designed for converting DC to three-phase AC, therefore, control strategies must be according to the three-leg three-phase power inverters. However, for MLIs, the control strategies must be inherited from three-leg three-phase power inverters. The control policies of VSIs in stand-alone mode can be categorized into numerous categories depending upon similar and dissimilar considerations. Considering the PWM, VSIs can be classified into two categories i.e., carrier-based modulation and carrier-less modulation. The carrier-based modulation schemes such as Selective Harmonic Elimination (SHE), 3D SVPWM, Sinusoidal Pulse Width Modulation (SPWM) and Minimum-Loss Discontinuous PWM (MLDPWM) based PWM techniques have attained significant consideration due to their constant switching frequency.

SPWM offers constant switching frequency and flexible control schemes; nevertheless, one major disadvantage of this technique is the compact efficacy of the DC voltage [148]. The 3D-SVPWM delivers an adequate DC bus utilization and a standardized load harmonic curvature as compared to the SPWM technique. However, it is complex in nature to be implemented on the digital devices. Correspondingly, the SHE-PWM suggests a flexible controller by considering the switching angle. However, the real-time enactment of this carrier-based modulation is quite difficult. The capability of the MLDPWM under nonlinear and unbalanced conditions is found relatively admissible; however, its real-time execution is found very much circuitous. However, the carrier-less modulation approaches such as flux vector and hysteresis provide a rapid-dynamic response [149]. But, they suffer from variable switching frequency [91]. Additionally, they require composite switching tables for their implementation.

The conventional PI controllers encounter problems to eliminate the steady-state error. In order to solve this problem, a PR controller is commonly used in the stationary reference frame for regulating the output voltages of the VSIs due to its sophisticated explication in eliminating the steady-state error, while controlling sinusoidal signals. Additionally, it is competent in eliminating selective harmonic uncertainties.

It is also taken into consideration that the PR controller perceives the resonant frequency to offer gains at specific frequencies. Thus, the resonant frequency should be synchronized with the frequency of the microgrid. Hence, it can be said that it is very sensitive with respect to the variations in system frequency. The PI controller is also extensively used in the  $dqo$  frame and performs robustly with pure DC signals. Though, in order to allocate the control variables from the  $abc$  to the  $dqo$  frame, the phase angle of the microgrid should be known. Likewise, using cross-coupling and voltage feedforward terms are the secondary problems in implementing this method.

In the stand-alone operating mode, VSIs primarily controls the power transfer, voltage and frequency of the system. Nevertheless, power quality can be enhanced by offering a suitable control technique in the inverter-based type DGs. As in VSIs, the auxiliary services for improvement in power quality embedded in the control assembly. In case of VSIs, compensation of unbalanced voltage, a lower value for total harmonic distortion, harmonic power-sharing schemes, power sharing between active/reactive powers, imbalance power, active/reactive power control and augmentation in power quality are critically considered and embedded in control schemes. VSIs are also applied on several applications in microgrid systems, extensively, for improving the power quality. This power control strategy is presented in [38]. However, a comprehensive review of various control strategies for microgrids is described in [150]. Moreover, using modular multilevel inverters can improve the modularity and scalability to meet reference voltage levels, efficiency in high power applications, reduction in harmonics in high voltage applications and size of passive filters as well as no requirement for dc-link capacitors [151].

In Table 3, different types of filters are suggested by various researchers based on the control systems. However, it is significant to use L-filters for low power applications having a simple design, nevertheless, L-filters are not found suitable in resonance state as well as for high power applications. So, LCL-filter is highly preferred in aforementioned system characteristics. The designing of this filter is comparatively complicated due to a few constrictions related to the system stability. The accuracy in designing and modeling of the system leads to better performance against resonance and harmonics. Nevertheless, the choice should be made according to the customer's demand. The prime parameters should be chosen on the basis of system condition and intended tasks to be performed by the system. Afterward, the designing of power system and control system parameters should be finalized.

This corresponding study incorporates the advantages and disadvantages of each controller in terms of stability, rapid response time, harmonic elimination, the nonlinearity of the system, unbalanced compensation and robustness against parameter variation. Various suitable control schemes for different types of VSIs are documented in this paper. However, their implementations for power generation and power quality improvement are still not perfect simultaneously. Moreover, each controller has its own benefits and obstructions. Therefore, it is not easy to decide that which control scheme is better than the others. These are significant subjects for the future research. On the basis of the analysis of former publications, appended research is suggested to be carried out in the aforementioned area.

Regardless of the several investigations in this field, none of the proposed control techniques can be selected as an immaculate solution to meet all the requirements of power quality, i.e., harmonic/reactive/imbalance power-sharing and voltage unbalanced/harmonic/swell/sag and Interruption compensation at the same time. Therefore, further research should be focused on the novel power-electronics topologies to fulfill all aforementioned necessities simultaneously.

Three-phase three-wire VSIs are now a well-developed and mature research topic with respect to their hierarchical control. But on the other hand, control hierarchies are not as well established for ML-VSIs, as for three-phase three-wire VSIs. It may be beneficial to consider ML-VSI system, as well as the primary, secondary and tertiary stages, whenever a control scheme is to be designed.

Substantially, a lot of work is to be done for exploiting the new control approaches for ML-VSIs. In order to achieve enhanced performance, it is compulsory to use some innovative techniques such as robust, MPC and LQR control techniques.

It is also observed through a number of studies that coupling among the phases is neglected whenever controlling an ML-VSI by means of a conventional PI controller, which results in a reduction of the system's robustness. Hence, it can also be beneficial to implement decoupled phase voltage control to realize the referred response in time domain. A comparison of the credible research articles found in literature with respect to their control techniques, modulation schemes, control parameters, loop characteristics, employed filters and applications is described in Table 3.

### 13. Conclusions

On the basis of research, conventional multilevel inverter topologies given in the previous sections, general and asymmetrically constituted ML-VSIs have been also reviewed in this paper. Several new hybrid topologies can be designed through the combinations of three main MLI topologies. Besides the combination of topologies, the trade-offs in MLI structures can be dealt by using H-MLIs that is formed using different DC source levels in inverter cells. PWM strategies that generate switching frequency at fundamental frequency are also introduced for H-MLIs for the switching devices of the higher voltage modules to operate at high frequencies only during some inverting instants. Due to numerous applications of conventional MLIs and flexibility to design the hybrid MLI topologies, this paper cannot cover all utilizations with MLIs but the authors intend to provide a useful basis to define the most proper control schemes and applications. In addition to these, the fundamental design and control principles of MLIs have been introduced as a result of a detailed literature survey. This paper has been destined to provide a reference to readers and the results given in this paper can also be extended with experimental studies.

**Table 2.** Description of predictive controllers on the basis of their pros. & cons.

	<p>Deadbeat Control</p> <ul style="list-style-type: none"> <li>• -Modulator required</li> <li>• -Fixed switching frequency</li> <li>• -Low Computations</li> <li>• -Limitations not undertaken</li> </ul>
	<p>Trajectory Based control</p> <ul style="list-style-type: none"> <li>• -Modulator not required</li> <li>• -Variable frequency</li> <li>• -No cascaded structure</li> </ul>
Predictive Control	<p>Hysteresis Based predictive control</p> <ul style="list-style-type: none"> <li>• -Modulator not required</li> <li>• -Variable frequency</li> <li>• -Uncomplicated structure</li> </ul>
	<p>Model Predictive Control</p> <ul style="list-style-type: none"> <li>• -Modulator required in case of continuous control set (CCS) and not required in case of finite control set (FCS).</li> <li>• -Likewise, fixed switching frequency (CCS) and variable switching frequency exists in (FCS).</li> <li>• -Online optimization and simple designing is included in case of FCS.</li> <li>• -Constraints are considered in both cases</li> </ul>

**Table 3.** Digital control system characteristics in numerous credible scientific proposals.

Application	Controller	Filter	Ref. Frame	Feedback	Modulation	Ctrl. Parameter	Ref.
General	adaptive	LCL	Single Phase	Multi-loop	SPWM	V, I	[51]
General	Classic, PR	LCL	Single Phase	Multi-loop	PWM	I	[152]
General	Adp., Rpt.	L	Single Phase	Single-loop	SPWM	I	[105]
UPS	DB	LC	Single Phase	Multi-loop	PWM	V, I	[153]
General	Rpt.	LC	Single-Phase	Single-loop	PWM	V	[101]
General	Rpt C	LCL	Single Phase	Single-loop	PWM	I	[104]
DG	Classic	LCL	abc, $\alpha\beta$	Single-loop	PWM	V, P	[47]
DG	Classic	LC	abc, $\alpha\beta$	Multi-loop	SVPWM	V, I	[48]
DG	Classic	LC	abc, $\alpha\beta$	Multi-loop	SPWM	V, I	[49]
DG	Classic	L	abc, $\alpha\beta$	Single-loop	VLUT	V	[50]
General	DB	L	abc, $\alpha\beta$	Single-loop	PWM	I	[52]
APF	Adp., Rpt.	LC	abc, dq	Multi-loop	SVPWM	I	[53]
General	DB	LCL	abc, dq	Multi-loop	PWM	I	[54]
DG	Adp., MPC	LCL	abc, $\alpha\beta$	Multi-loop	SVPWM	I	[55]
General	LQG	LCL	abc, dq	Single-loop	PWM	I	[66]
PV	PR, LQG	L	abc, $\alpha\beta$	Single-loop	SVPWM	I	[64]
General	Adp.	L	abc, $\alpha\beta$	Multi-loop	PWM	I	[107]
UPS	Pred.	LC	abc, dq	Single-loop	SVPWM	V	[109]
PV, APF	Pred., Fuzzy	L	abc, $\alpha\beta$	Multi-loop	PWM	P	[108]
PV, APF	SMC, Pred.	L	abc, $\alpha\beta$	Multi-loop	PWM	P	[111]
General	DB	L	abc, dq	Single-loop	SVPWM	I	[113]
General	Adp., DB	L	abc, dq	Single-loop	PWM	I	[112]
DG	DB	L	abc, dq	Single-loop	SVPWM	I	[116]
UPS	DB, Rpt.	LC	abc, $\alpha\beta$	Single-loop	PWM	V	[115]
General	MPC	LCL	abc, abc	Single-loop	PWM	V, I	[122]
General	MPC	L	abc, $\alpha\beta$	Single-loop	PWM	I	[125]
General	MPC	L	abc, dq	Single-loop	SVPWM	I	[128]
PV	MPC	L	abc, dq	Single-loop	SVPWM	I	[130]
PV	Classic, Rpt.	L	abc, dq	Single-loop	SVPWM	I	[97]

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