Review on Current Control Techniques of Grid Connected PWM-VSI Based Distributed Generation

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ABSTRACT

Nowadays, new trends in the industry of electricity generation are to enhance the power generation by employing a distributed generation (DG) system which is mostly based on renewable generation sources such as wind, solar, etc. However, many power quality problems could arise on the existing grid when DG is connected or the operation of distributed energy resources (DER) is not controlled properly. That's why, while integrating DG with the power grid, a seamless attention should be given to power generation and safe running of the system. Several methods, having diverse concepts, have been divided into two main sets: linear and nonlinear controllers. The first group comes with a PI controller and a parameter feedback controller, and controls by means of the constant frequency with predictive techniques. The second group includes hysteresis current control and on-line optimization for predictive controllers. Additionally, new current control techniques with neural networks and fuzzy based controllers are also discussed. These control methods are detailed in this paper to describe all the arrangements of linear and nonlinear control techniques.

Keywords: Distributed Generation (DG), Current Control, Distributed Energy Resources (DER), PWM-VSI

1. INTRODUCTION

The demand for electricity is globally increasing every year at the rate 1.9% on average from the year 2012-2040 [2]. With the aim to reduce greenhouse gasses as per the Kyoto Accord protocol, the increasing demand for electricity generation cannot be met with conventional power generation sources alone [3]; that introduces an opportunity for distributed generation (DG) systems. Nowadays, DGs are mostly based on renewable energy sources (RES), as these sources have a major contribution in meeting growing energy demand. From RES the share of wind energy and solar PV generation in the previous decade can be checked from [4, 5].

However, due to the variable nature of the output power of these RES, their control is the utmost issue when they interconnect with utility system [6]. The most commonly used power electronics-based strategy to connect DG with power grid is by using a pulse width modulated voltage source inverter (PWM-VSI). VSI is the main focus in DG connected systems; it controls the power optimization parameters and satisfies. the requirements of grid interconnection and power quality [7]. The current controller for VSI connected with the grid is responsible for maintaining the quality of power which is being fed to the power grid by DGs [1].

Various current control strategies for three-phase VSI have been proposed in [8-15]. Usually, the PWM-VSI used for DG system have same current control structure with an inner current feedback loop which is used for active power filter, UPS, and VFDs. The two main tasks of VSI are to compensate for the error in current and generate PWM signals [1]. The two main types of current control strategy of PWM-VSI are classified as, closed-loop nonlinear controller and open loop linear controller [16]. The overview of these controllers is shown in Fig. 1.

The Hysteresis Current Controller (HCC), is a nonlinear current controller which has been extensively used for grid-connected VSI systems [17]. HCC controller is easy to implement in a system, with very fast speed of feedback current loop that is independent from the nature of the load [18]. This controller has fast dynamic response and high current protection as compensation for current and generation of PWM pulses are controlled by the same control unit and error in current is directly employed for generation of the next pulses [19]. However, this controller produces high current ripples and has variable switching frequency, which results in poor quality of current and causes difficulties in designing the output filter [1].

A space vector pulse width modulation (SVPWM), from linear current controllers, is being widely utilized to control PWM inverter [20-22]. SVPWM

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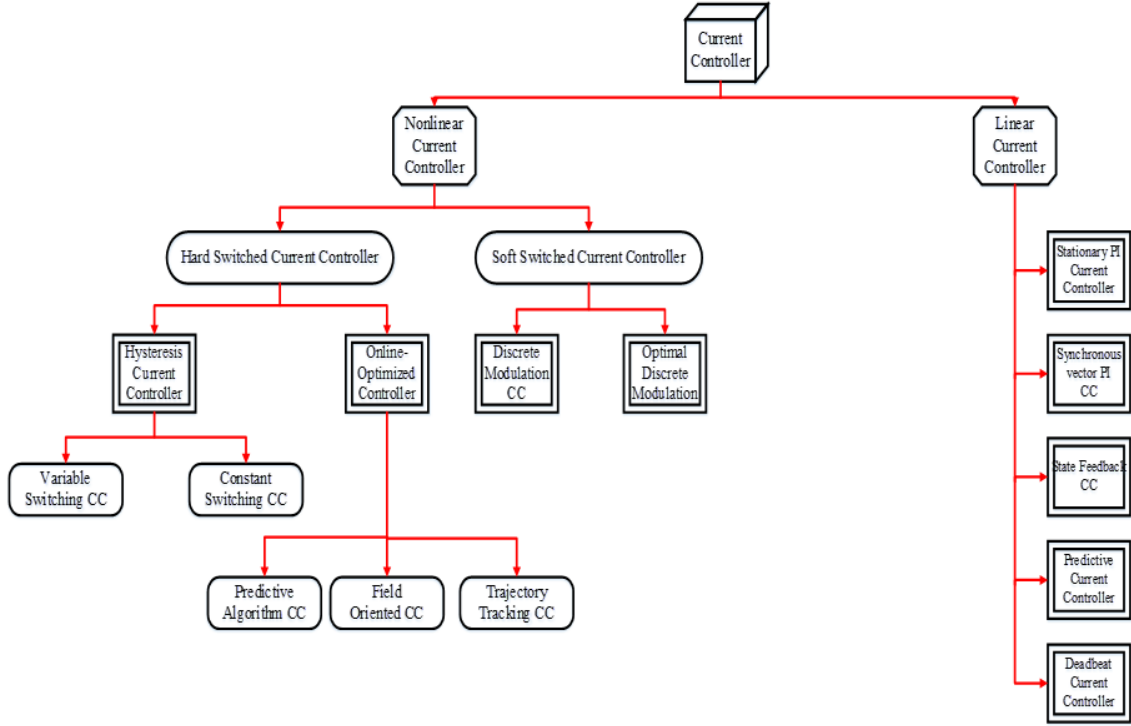
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Fig.1: *Types of current controller.*

separately functions for current compensation and pulses generation, making possible advantages to exploit this controller and design the structure of the controller independently. The constant switching frequency, controlled THD levels, optimal switching signals and utilization of dc-link voltage, etc. are the main advantages of SVPWM [1, 23]. The detailed discussion of both types of the controller is given in the sections below.

Consecutive sections of this paper are divided as, Section 2 is dedicated for linear controllers, in Section 3 nonlinear controllers are discussed, whereas Section 4 contains the conclusion and recommendations.

2. LINEAR CURRENT CONTROLLERS

This type of current controller works with the conventional type of voltage PWM modulators [24-30]. In comparison with the nonlinear controllers, the structure of linear controllers has independent compensation for current error and modulation part. This type of controller structure allows us to achieve the benefits of open-loop PWM controller (sinusoidal modulator error between line current i_A, i_B, i_C and reference current i_{AC}, i_{BC}, i_{CC} which is set by the system operator). The amount of ripple is associated with proportional gain and zero placement of the PI regulator. The voltage vector is then compared with a triangular carrier signal in order to generate switching pulses S_A, S_B and S_C for VSI. If the slope of voltage [31], space-vector PWM [32], and optimal PWM modulator [33]). These controllers have a constant

frequency of switching, a distinct spectrum of harmonics, optimal switching pattern, and utilization of dc-link voltage. Further, the design of overall full independent structure of controller allows easy open loop testing of the inverter as well as the load. In the group of linear controllers, the following controllers are defined: stationary and synchronous PI controller, state feedback controller, and predictive controller with constant frequency switching.

2.1 Stationary PI current controller

The stationary PI current controller, also known as the ramp comparison, uses three error compensators based on a PI regulator in order to generate three voltage vectors (u_{Ac}, u_{Bc}, u_{Cc}) used for three-phase sinusoidal PWM as shown in Fig. 2(a) [34, 35]. Keeping in view the principle of sinusoidal PWM, the output of the PI controller is compared with a triangular signal for generation of control signals for switches of inverter. Meanwhile, the output of this controller is being directly derived from the original sub-oscillation of a triangular signal [36, 37]. However, the performance of the controller is not suitable for this operation, because the ripples in output current are fed back which effects the switching periods.

In this type of controller, the role of an integral part of the PI controller is to minimize current error at low frequency (i.e. exceeds the triangular signal slope, then additional complications may arise from multiple crossings of boundaries. The consequences of this controller are that its performance will be sat-
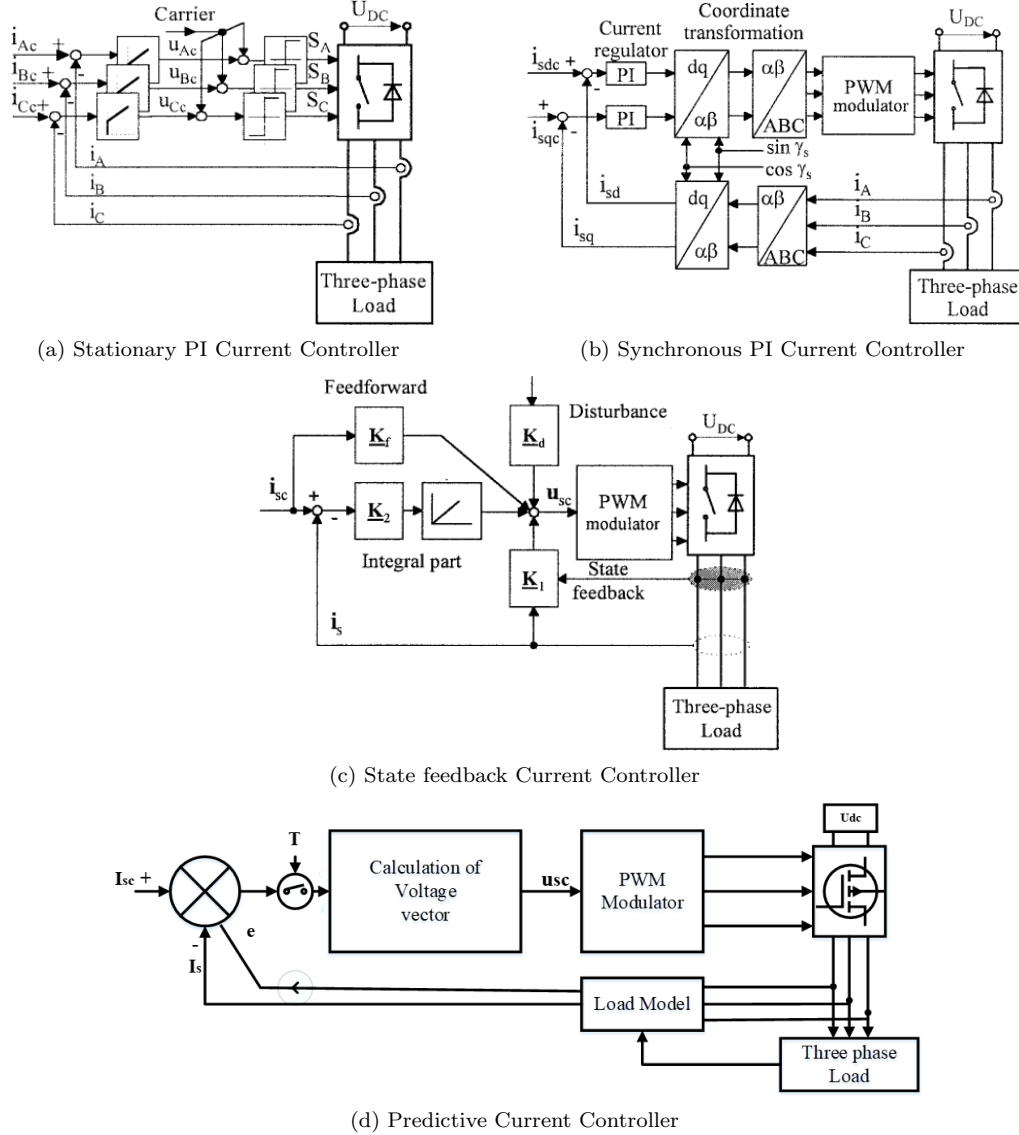
(a) Stationary PI Current Controller

(b) Synchronous PI Current Controller

(c) State feedback Current Controller

(d) Predictive Current Controller

Fig.2: *Linear current controllers (a) stationary PI, (b) synchronous PI, (c) state feedback controller, and (d) predictive controller [1].*

isfactory if harmonic contents in current and load voltage are under the frequency of triangular carrier signal (less than 1/9 [23, 38]). The inherent tracking of error for compensation is the core weakness of this strategy. In order to attain satisfactory compensation, additional phase-locked loop (PLL) circuits have been proposed in [39] or utilization of feedforward correction also suggested in [40].

2.2 Synchronous vector PI current controller

In a system, where an ideally controlled current is mandatory for its reliable operation, even a minor phase or magnitude error may cause inappropriate system operation. For example, in case of ac motors with vector controlled technique, the space vector based control approach can be applied. The synchronous PI controller structure is given in Fig. 2(b), in which components of the current vector are defined

in rotating coordinates and is compensated by two PI regulators [41-45].

With the help of coordinate transformation, the measured load currents (i_A, i_B, i_C) are converted to dq axis $(i_{sd}$ and $i_{sq})$ and compared with dc component of error $(i_{sdc}$ and $i_{sqc})$. The PI controller reduces the error between the fundamental components to nearly zero. The Park's and Clarke's transformations are obtained using Eqs. (1) and (2), respectively.

$$
\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_0 \end{bmatrix} =
$$

$$
\sqrt{2/3} \begin{bmatrix} \cos\gamma_s & \cos(\gamma - \frac{2\pi}{3}) & \cos(\gamma + \frac{2\pi}{3}) \\ -\sin\gamma_s & -\sin(\gamma - \frac{2\pi}{3}) & -\sin(\gamma + \frac{2\pi}{3}) \\ 0.707 & 0.707 & 0.707 \end{bmatrix} \cdot \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (1)
$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \quad (2)$$

It has been established in [34], that control of current vector is possible in arbitrary coordinates; based on this a system with stationary coordinates $\alpha - \beta$ of ac components has been controlled with asynchronous PI controller in [33]. Overall performance of PWM controllers gave a definite spectrum of harmonics available, but its dynamic performance is worsened as compared to hysteresis controllers.

2.3 State feedback current controller

The compensation part of the conventional PI regulator in compensating current error can be exchanged by a state feedback current controller, working in stationary coordinates [46] or synchronously rotating $(d-q)$ [47, 48]. The controller is shown in Fig. 2(c) working in $d-q$ coordinates and is incorporated on the properties of linear multivariable state feedback theory. By utilizing pole assignment strategy, feedback gain matrix K_1 and K_2 are derived in order to ensure necessary damping. The static error can be reduced to zero with use of integral part K_2, but unacceptably a large transient error may occur. So, K_f a feedforward reference signal and disturbance K_d are given to feedback control to reduce transient. As this control algorithm ensures the correct dynamic compensation for the voltage, hence the performance of this technique is better as compared to conventional controllers [30].

2.4 Predictive and Deadbeat current controller

The procedure of this technique is that it predicts the error current vector at the start of each sampling period based on actual error and load side parameters. The consecutive voltage vector generated by PWM throughout the successive modulation periods is thus determinate, in order to minimize the forecast error and hence generating voltage vector U_{sc}. Further, the U_{sc} is utilized to produce gate pulses [49-51]. In [52] a Hybrid current controller is proposed using a predictive and hysteresis controller.

2.4.1 Predictive current controller with constant frequency switching

In the controller shown in Fig. 2(d), the voltage vector command $\boldsymbol{u}_{sc}(T)$ is calculated by predictive algorithm for every sampling time T. By this the current vector $\boldsymbol{i}_{sc}(T)$ will be forced to follow the command vector.

During the sample time T, load voltage $\boldsymbol{e}(T)$ and inverter voltage $\boldsymbol{u}_s(T)$ are assumed as constant. The $\boldsymbol{u}_{sc}(T)$, calculated voltage vector is then applied in the algorithm of PWM modulator, e.g., space vector [53-56] or sinusoidal modulator [56]. Note that, the inverter switching frequency will be fixed until current ripples occur. The main drawback of this controller is that it does not guarantee the limit of inverter peak current.

2.4.2 Deadbeat current controller

When there is a choice to null the error in voltage vector at the end of the sample period, that strategy is often known as deadbeat controller [51, 57]. For the operation of this controller, additional information is given to the controller such as non-available parameters (speed and flux). For determination of voltage vector, this requires utilization of an observer or some control blocks, which may be shared with the scheme of the controller, as in the case of ac machines [58, 59].

3. NONLINEAR CURRENT CONTROLLERS

The group of nonlinear current controllers consists of hard and soft switched controllers, Discrete Modulation current controller (DM-CC), and on-line optimized parameters controller. The category of nonlinear controllers also includes Neural Networks (NN's) and Fuzzy Logic Controllers (FLC's) based current controllers. The detailed description of these controllers is given below.

3.1 Hard switched Current Controller

This type of controller comprises of Hysteresis current controller (HCC) with variable and fixed switching frequency. Further details of both these types are given as under.

3.1.1 Hysteresis current controller

The scheme of the HCC controller is based on a feedback loop along with hysteresis comparator of two levels [60]. The HCC generates switching signals for VSI when the error between the measured value and a set reference value exceeds tolerance band H as shown in Fig. 3 [61].

3.1.1.1 HCC with variable switching frequency

There are several advantages of HCC, such as it is simple to interface, dynamic performance, independent of changing load parameters and of tracking errors, and extremely good performance in controller peak to peak ripples in current within a specified band. This type of HCC is known as free runner HC [62], but it has some drawbacks. These are; it generates an uneven switching frequency, as it largely depends on parameters of load and it directly varies as a change in AC voltage. Due to this it possibly produces unwanted resonance on power system [63, 64].

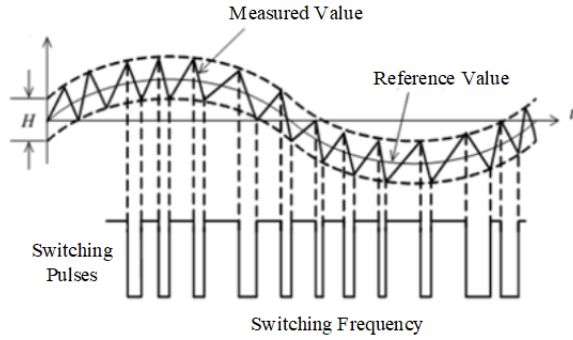Further, because of irregular switching patterns, it is difficult to design a protection scheme for the

Fig.3: *Pulses generation by hysteresis current controller.*

converter [65, 66]. One of the characteristics of HCC is that its instantaneous current is exactly kept inside the tolerance band, apart from the systems with no neutral, where the value of the instantaneous error is approximately twice that of the tolerance band [67, 68]. It is due to the interfacing of the system with three different controllers. If in one phase state of comparator changes it will affect the supplied voltage to the load in the remaining phases. However, the coupling effect of the comparator can be compensated for if all these errors in current are advised as space vectors [69], and further modified space vector based controllers can be designed [70-75]. As discussed in [71-74, 76] if the lookup table is used with these three level comparators, the frequency of inverter switching can be decreased considerably.

In $d-q$ synchronously rotating coordinates, there is a rectangular error field, due to which independent harmonics can be selected by the controller separately for d and q components [77, 78]. This technique can be used in vector controlled motor drives for minimizing torque ripple (the flux current components for torque current is higher than hysteresis band value) [77, 79].

3.1.1.2 HCC with constant switching frequency

Several researchers proposed techniques to overcome the drawbacks of variable switching frequency controllers [80-85]. The constant switching frequency controller has a fast-dynamic operation and tackles the weakness of the variable switching frequency hysteresis controller. The concept of constant switching frequency is founded by predicting the reference current, dynamic behavior of system, and previous state of operation of system in order to pattern the function of switching for inverter switches inside a predefined period of switching.

Another point worth noticing is that in implementing hysteresis control, an adaptive band controller have been designed to acquire constant frequency switching. A number of techniques and processes have been discussed in [86-89] for calculation of switching frequency. As per the literature, constant switching HC operation is more complex as compared

to variable frequency HC, but the output enables a fast response along with precise tracking of the error. Hence, HC with constant switching frequency is best suited for a system with the fast speed of operation and high dynamics applications [90].

3.1.2 Current controller with On-line optimization

The performance of these types of controllers mainly depend on real-time optimization techniques and intricate calculations are involved, for which microprocessor can be implemented. Further categories of this type of controller are discussed below.

3.1.2.1 Predictive algorithm with minimum switching frequency

The predictive algorithm is based on analysis of hysteresis controller by space vector [91, 92]. In case of the independent controller with tolerance band having same value for all phases will delimit the area of current error and makes a symmetrical regular hexagon as shown in Fig. 4(a). If suppose one hysteresis controller is utilized and stand-in with the vector of current error, the switching pattern or curve for error or the boundary area of error might have a shape as shown in Fig. 4(b). The vector of current command i_{sc} determines the error curve location. When a point is reached on current error curve by the current vector in different trajectories, then seven paths (one zero and six active) of the current are predicted.

From seven of them, one for each will output voltage vector. Lastly, following the procedure of optimization, the mean switching frequency of inverter which is minimized by voltage vector will be selected as shown in Fig. 4(c). For the condition of fast transient states, such optimization techniques should be applied which minimizes the response time [1].

In comparison with the conventional cascaded controller, the predictive control is a virtuous substitute [93]. From one of the advantages of the predictive controller is a nonlinear system can be presented in a better way, the option to utilize the recognition of drive system and usually no requirement for a cascade structure.

3.1.2.2 Field-oriented current controller

The current controller with a predictive algorithm for minimum switching can be applied to any system of coordinates (stationary or rotating). These are identified as working of hysteresis controller in three-level field-oriented coordinates [77, 94]. Hence, by selecting rectangular error curve in this controller if used in ac machines, a significant reduction in switching frequency can be achieved by having higher reluctance in direction of rotor flux [95].

Practically, prediction and optimization process needs more time to predict switching frequency. Therefore, there is a need to use algorithms which are faster with dynamic performance. One technologically advanced technique uses two active voltage
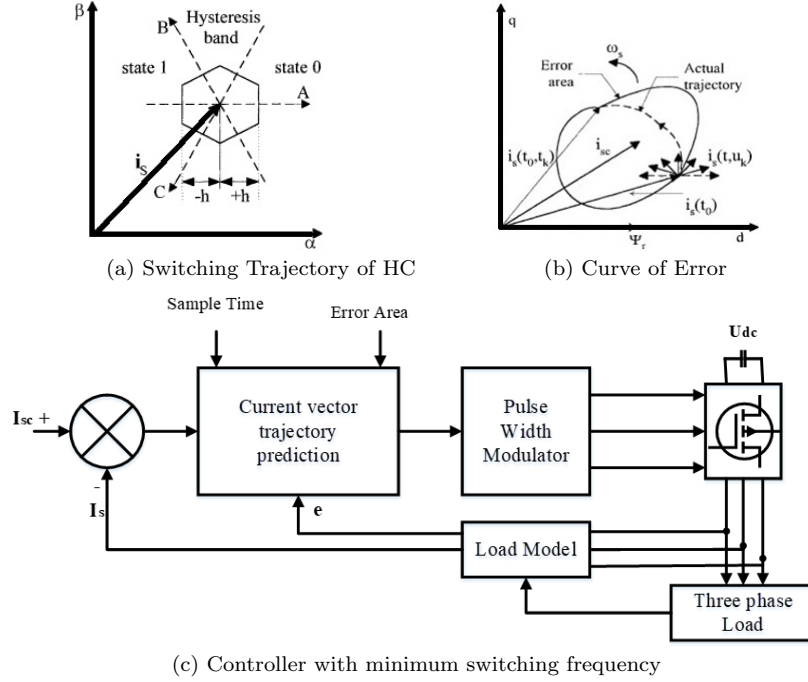
(a) Switching Trajectory of HC

(b) Curve of Error

(c) Controller with minimum switching frequency

Fig.4: *Hysteresis controller (a) switching trajectory, (b) curve of error, and (c) controller with minimum switching frequency [1].*

vectors from predicted vectors and the zero voltage vector in order to optimize without compromising on quality [96, 97].

3.1.2.3 Trajectory tracking control

This technique was first proposed in [98, 99]; it compensates dynamic tracking error of current in converters by combining an off-line optimization for steady-state operation of PWM pattern with an on-line optimization. With this technique system with low switching, frequencies can achieve very good steady-state and dynamic performance.

In [100], researchers analyzed this technique with modular multilevel converters (M2Cs) where they exploited the properties of the converter with the differential flatness of the model of the load. This is done by assuming the subsystem of a load connected to the converter as a current source. The suggested controller accompanied a planning algorithm for trajectory and a controller for tracking. In this way, the modeling leads to a decoupled load controller resulting in a converter controller and tracking controller.

3.2 Soft switched (Resonant DC Link, RDCL) current controllers

In three-phase RDCL soft switched converters with zero voltage switching (ZVS), the process of commutation is limited to only discrete time intervals T, where the value of voltage pulses for dc-link is zero. Hence, designated strategies such as delta modulation (DM) or pulse density modulation (PDM) can be used [101-108].

3.2.1 Discrete modulation current controller (DM-CC)

The basic structure of DM-CC is shown in Fig. 5(a). With regard to its internal structure, it looks similar to HCC but its operational principle is relatively different [109-112]. In DM-CC, the comparator perceives the error sign only, and the outputs at a fixed rate are sampled; thus, during each sampling time interval, the inverter output is kept constant. Hence, only a voltage vector is generated by the converter at a fixed time without using PWM. This controller produces a discretized output voltage of the inverter, unlike continuous voltage, as one of the features of PWM.

Discretization of voltage has a negative impact that is, an imperceptible amount of subharmonics is generated while synthesizing the periodic waveforms [113, 114]. In order to obtain an indistinguishable output, DM-CC should be switched at a seven times higher frequency compared to PWM modulator [113, 115]. Nevertheless, this controller is simple in design and is independent from the parameters of the load. When DM-CC is applied to 3-ϕ inverters with a load having insulated neutral, the interference of phases and the freedom in selecting the voltage vector must be considered. Consequently, rather than performing separately the delta modulation for control of each phase, voltage output vectors are selected depending not only on the voltage error vector, but also on the previous standing in order that the zero voltage switching gets to be distinctly conceivable [116, 117]. The limiter is utilized here to minimize the error
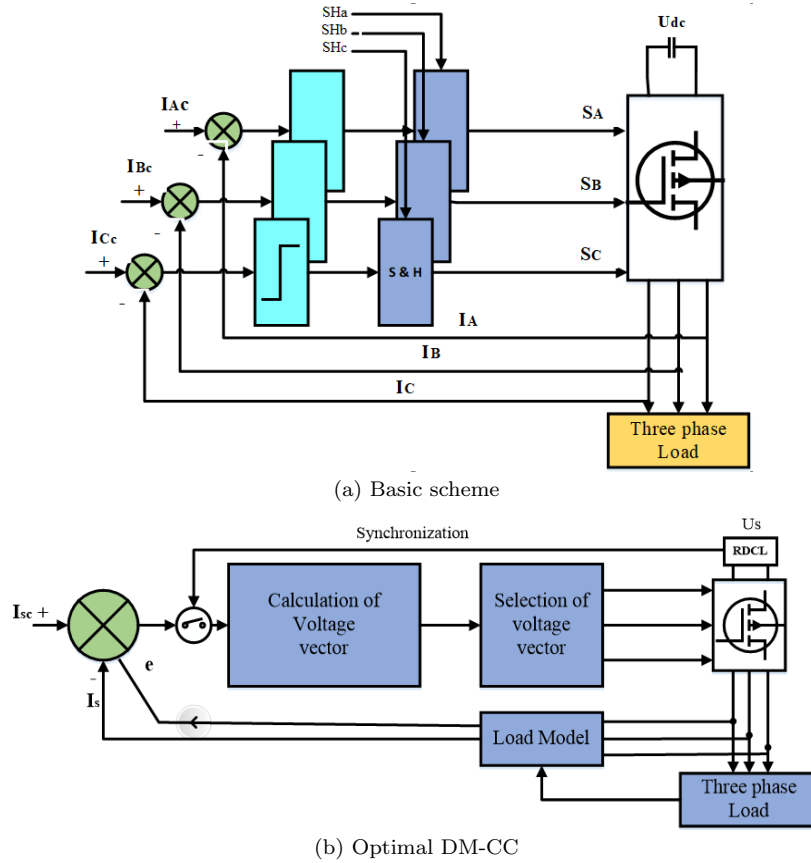
(a) Basic scheme

(b) Optimal DM-CC

Fig.5: *Discrete modulation current controller (a) Basic scheme, (b) Optimal DM-CC.*

between measured current (I_{AB}, I_{BC}, and I_{AC}) and load current (I_A, I_B and I_C). S & H blocks are the sample and hold blocks, used as a comparator and to limit the switching frequency to sampling frequency. Whereas, sample and hold signals (SH$_A$, SH$_B$, and SH$_C$) are generated based on load parameters, dc-link voltage (U_{dc}), inverter input voltage and sampling frequency. Further, the switching pulses (S_A, S_B and S_C) for VSI are then generated based on the measured sample and hold signal and error between currents.

The DM-CC is also compatible with controllers based on the space-vector technique, working either in rotating or stationary frames [118]. Among the foremost advantages of this controller are that it is exceptionally simple in operation with no requirement of tuning hardware and it attains satisfactory dynamics [119, 120].

3.2.2 Optimal Discrete Modulation current controller

In order to get optimum results from the RDCL converters, an optimal algorithm has been proposed which selects the voltage vector to minimize the error of *rms* current for every resonant pulse [80], [93], [106]. As discussed in [106], this technique is equivalent to selecting the available voltage vector command $u_{sc}(T)$ which is nearest to the solution. Accordingly,

only the voltage vector selector is needed as shown in Fig. 5(b) and a substitute to the PWM modulator as in Fig. 4(c).

4. ARTIFICIAL INTELLIGENCE BASED CURRENT CONTROLLER

In recent times, new evolving tools of artificial intelligence such as Neural Networks and Fuzzy Logic controllers have been utilized for controlling current in PWM modulator. Further description of these strategies is given below.

4.1 Neural Network (NN) based current controller

The parallel processing of data, the ability of learning, sturdiness, and generality are the main advantages of using a neural network as a controlling tool for PWM. All these abilities of NN are effective for a current controller [121-125].

The NN is a simple technique when applied with PWM as shown in Fig.6(a), which excludes the need for on-line calculations required to implement optimal DM-CC [125], as shown in Fig. 5(b). Further, the performance of the NN controller depends on the trained data. In [125], the authors trained the data gained from the output of Fig. 5(b) before utilizing the NN as a controller. The results achieved from

the NN are better as compared to optimal DM-CC. Hence, the controller based on a NN can be utilized to regulate output current of the PWM converter, without the requirement of on-line calculation as required in optimal DM-CC.

With the approach considered by [125], there is no further possibility of training the NN during operation of the controller. Consequently, an off-line trained NN controller's performance depends upon the quantity and superiority of trained data and its performance is affected by variations in parameters [126]. For systems which need to compensate variations in parameters, an on-line trained controller can be useful. In [127], authors proposed a controller for controlling the speed of the permanent magnet synchronous machine (PMSM) based on a NN. The robust controller was designed to cope with parameter variations of the selected system, considering torque control loop time, inertia and coefficient of torque of the motor. The operation of the controller was based on on-line parameters tuning considering control of speed error. The output of the controller was fast with a precise algorithm for tuning the NN structure. Better results were achieved by elaboration of a fast and precise training algorithm and proper structure of the NN. The structure of the controller is considered as an adaptive speed controller for PMSM.

4.2 Fuzzy logic (FL) based current controller

Primarily, the fuzzy logic controller is utilized as a replacement for the conventional proportional and integral controller [114], [118]. The principal block diagram of a fuzzy-tuned PI controller, together with the fuzzy inference system is shown in Fig. 6(b). The error in current 'e' error and its derivative 'Δe' are the input of FL controller. The output of FL controller is the reference voltage for the PWM circuit. With the application of FL as a CC, a significant reduction in tracking the error and overshoot of current can be achieved in PWM control.

DG units are summarized in Table 1. From the literature, it is evident that linear current controllers are more feasible than nonlinear current controllers. The effectiveness of each controller may be validated by utilizing this controller in real time software simulations before applying them on-site.

5. COMPARISON OF SIMULATED MODELS

A goal is to validate the performance of current controllers utilized for DG units. The system shown in Fig. 7(a) is considered for this purpose whereas, Fig. 7(b) is considered for three phase grid. Further, the ratings of the proposed system are given in Table 2. The intended system is initially operated in synchrony with three phase grid; at time $t = 0.5$ s the performance of the current controller is tested

Table 1: *Comparison of Current Controllers.*

Nonlinear Current Controllers	Linear Current Controllers
The internal structure is complex as, current error compensation and voltage modulation operate at same time.	The control is simple as current error compensation and voltage modulation are separate parts.
They achieve good dynamic response, but steady state time is worst.	They achieve excellent steady-state response and overall performance.
They produce large current ripple.	They have low current ripples.
Attain high THD value.	Generate high-quality waveform.
They have complex protection scheme for when used for VSI.	It can be implemented with modern artificial intelligence techniques to further improve system behavior.
The output of artificial based CC is slow.	With application of optimization technique, their output become fast.

when the grid is disconnected and VSI connected PV system is supplying independently. The anticipated current controllers are also tested when the three phase load is decreased from 4 kW to 2.5 kW at time $t = 0.7$ s. The considered model is tested separately with linear and nonlinear current controllers and the achieved results are measured in p.u. system (1 p.u. is considered as reference voltage) [128] and discussed in subsequent subsections.

5.1 Simulation result of Linear current controllers

All the types of linear current controllers are tested accordingly. At first, the stationary PI current controller is initially tested with fixed gain values as shown in Table 2 [129]. Synchronous vector PI CC as discussed in [26], state feedback CC as in [130], Predictive CC as in [53, 131] and deadbeat CC in [57] are utilized in this study for comparison studies.

Fig. 8(a) shows the system rms voltage profile attained by utilizing a linear current controller. From the obtained results, it is evident that the deadbeat current controller achieves better results as compared to other controllers and has less overshoot and settling time. Furthermore, the total harmonic distortion in voltage and current is also under the limits specified in IEEE 1547-2003 standard [132] as mentioned in Table 3.

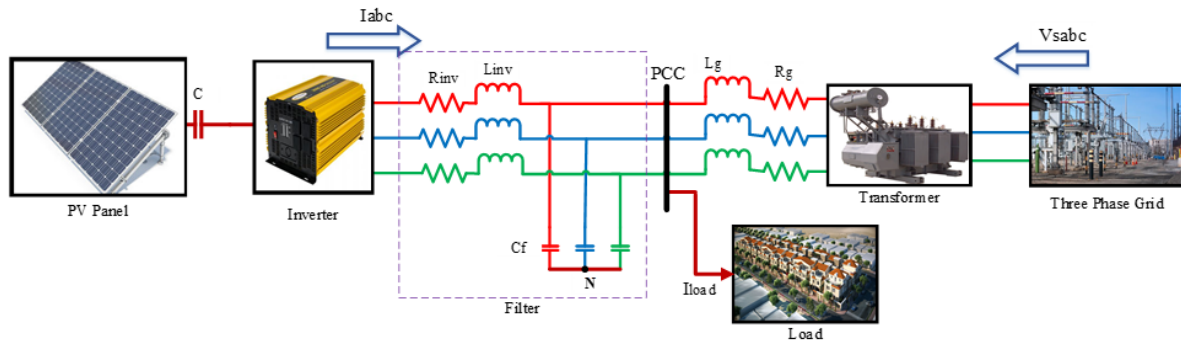### 5.2 Simulation result of Nonlinear current controllers

The nonlinear current controllers are also tested with the same grid connected PV system. Fig. 8(b) shows the output of hard switched current controllers; from the result, it is evident that constant switching
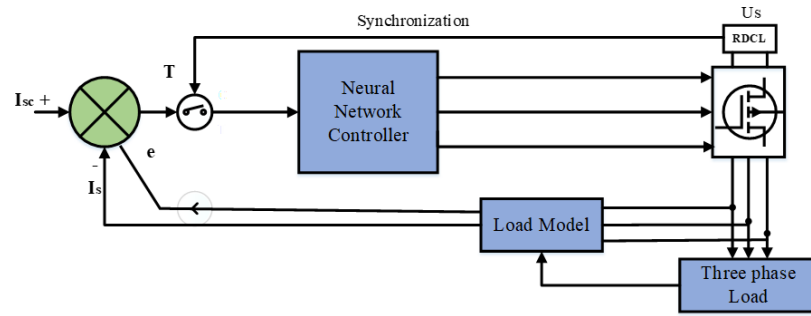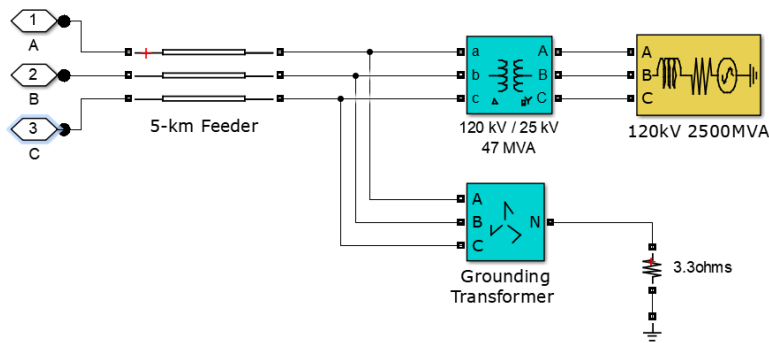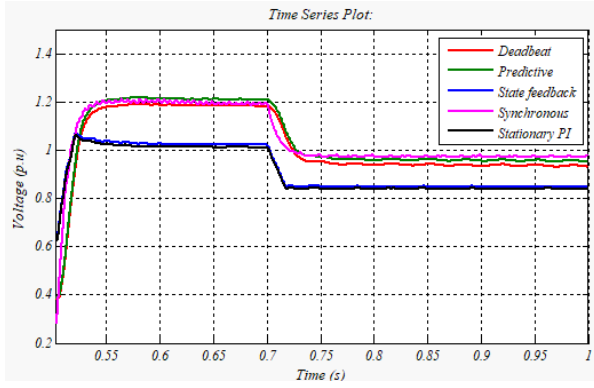
(a) Neural Network CC
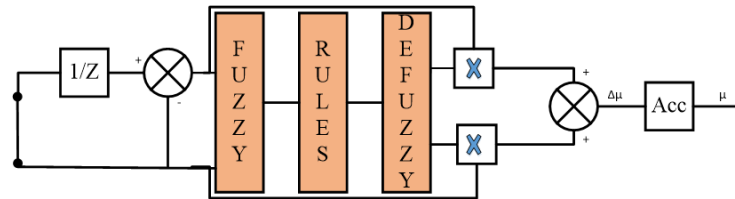
(b) Fuzzy Logic CC

Fig.6: *Artificial intelligence current controllers (a) neural network CC and (b) fuzzy logic CC.*
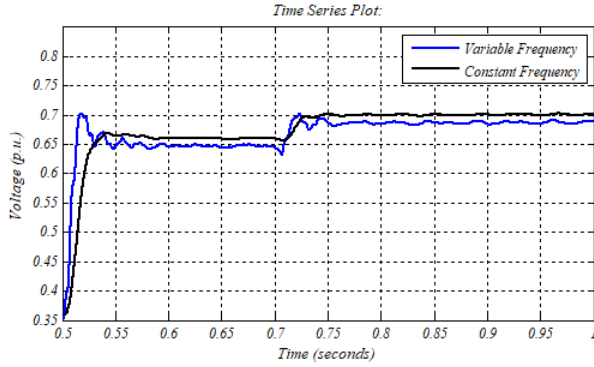

(a) Grid Connected PV panel
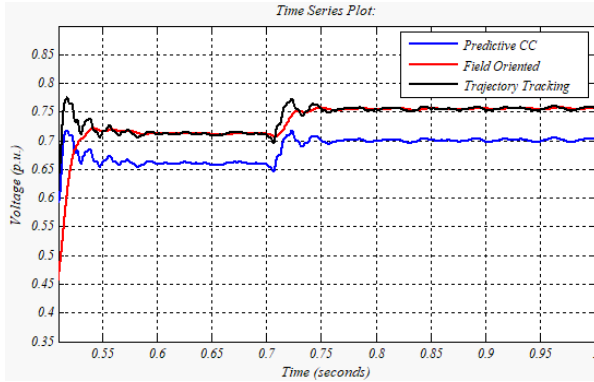

(b) Three Phase grid considered

Fig.7: *Considered Simulation Model (a) Grid Connected PV, (b) Three Phase Grid.*
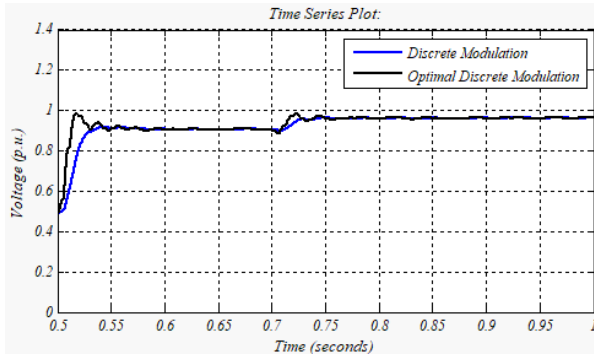
(a) Voltage Profile with linear current controllers

(b) Hysteresis Current Controller

(c) Online Optimized Current Controllers

(d) Soft Switched Current Controllers

Fig.8: *Voltage response of the System (a) linear current controllers, (b) hysteresis current controllers, (c) online optimized current controllers, and (d) soft switched current controllers.*

Table 2: *System Parameters.*

Grid Parameters	
Ls	50 mH
Rs	1.4 Ω
f	50 Hz
C	1500 μF
DC Capacitor (U_{DC})	5000 μF
One DG unit rating	50 kW
Current control loop parameter	
Kp	12.656
Ki	0.00215
SVPWM	
Switching frequency	10 kHz
Sampling frequency	500 kHz
PV Model	
Output Power	510 W
DC voltage output	103.2 V
Three Phase Load	4kW

CC is achieving better results as compared to variable switching CC [133]. However, constant switching CC has higher transients at times when the load increases but its settling time is small as compared to variable switching CC. Their THD levels are displayed in Table 3.

Further, the output of rms voltage achieved by online optimized CC are given in Fig. 8(c). From the attained results, it is clear that the trajectory tracking CC [98] achieves better results as compared to field oriented and predictive algorithm CC [52]. The rise time is more in the case of trajectory tracking CC but the overall performance is better when compared with other controllers in this category. The harmonic distortion in current and voltage achieved are also given in Table 3.

Finally, the performance of soft switched CC is checked under the same system. The output shows that the optimal discrete modulation CC [134] provides overall better performance in comparison to discrete modulation CC as can be seen from Fig. 8(d). Their voltage and current harmonic levels are given in Table 3.

6. CONCLUSION

In this paper a thorough review on current control techniques used for PWM-VSI have been discussed. These controllers are divided into two categories: linear controllers (stationary PI, synchronous PI, and predictive deadbeat controllers) and nonlinear controllers (hysteresis CC, discrete modulation, and online optimized controllers). The base principles and the up-to-date advances of these controllers have been thoroughly discussed in this paper. The points of interest and limits have been briefly observed, and the systems where these techniques are principally appro-

Table 3: *Total Harmonic Distortion of system.*

Technique	Voltage			Current		
	Line THD (%)			Line THD (%)		
Linear Current Controller						
Stationary PI	3.59	3.45	3.65	4.2	4.15	4.36
Synchronous PI	3.41	3.39	3.61	4.18	4.21	4.4
State Feedback	3.21	3.25	3.45	4.05	4.15	4.21
Predictive CC	3.26	3.12	3.15	4.0	3.85	3.98
Deadbeat CC	3.1	3.05	3.1	3.8	3.82	3.6
Nonlinear Current Controllers						
Variable Switch	3.6	3.55	3.53	4.41	4.35	4.32
Constant Switch	3.5	3.51	3.48	4.39	4.32	4.3
Predictive	3.51	3.5	3.52	4.32	4.3	4.28
Field Oriented	3.54	3.52	3.54	4.25	4.27	4.2
Trajectory Tracking	3.45	3.42	3.5	4.19	4.2	4.15

priate have been specified.

In summary, the new trends in research support wholly digital control. Therefore, the controllers which are appropriate for digital control are preferred, even though there is some sacrifice in dynamic performance and accuracy of the system. Specifically, for equipment with heavy diffusion and low-performance applications (blowers, fans, pumps), a PI regulator with digital control is suitable. For systems with high-performance criteria such as high-power units and traction machines, on-line optimized and linear predictive controllers are preferred. An improved version of hysteresis controllers is appropriate for quick, precise conversion systems such as filters.

It is conceivable that NN's and FL-based CC methods can offer another intriguing perspective for future research. At present, nonetheless, they represent only an alternative to existing techniques of CC, and their exact applications zones cannot be clearly characterized.

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