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Current control techniques of single phase shunt active power filter- a review

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Abstract. This manuscript gives a complete survey on current control for single phase Shunt Active Power Filter (SAPF). Various current control techniques like linear current control, Hysteresis, Model Predictive Current Control (MPCC) and other techniques are discussed. The primary advantages and disadvantages of current controllers in SAPF have been presented in a table. This manuscript offers a suitable reference for forthcoming work in power quality applications and its associated research.

1. Introduction

In distribution network the power quality problem is mainly due to the nonlinear loads. The NLLs like uninterruptible power supplies, Grid-connected inverters, light controllers, electric furnaces, temperature controllers, solid-state ac voltage regulators, and arc furnaces cause power quality problems at the consumer ends. Because of the nonlinear loads the major problems in the power sector applications like overheating of the transformer, machine vibrations, inaccurate power metering and disturbance to nearby communication networks [1-4].

In order to improve the power quality conventional solution passive filters used which is of low cost, simple complication and improved efficiency, but still has major drawbacks like fixed compensation, huge size and resonance problems. So, to overcome the above mentioned cons the most effective technique for improving power quality the use of Shunt Active Power Filter (SAPF) is preferred.

The SAPF concept was firstly proposed in 1971 by Sasaki and Machida for removing current harmonics [5]. The SAPF operate in different operating conditions and higher frequencies effectively, which leads to giving enhanced performances. The general aim of a SAPF is to reduce harmonic distortions caused by non-linear loads and improve power factors for reactive loads. The single-phase active power filter is typically used in lower power ratings. It is suitable for educational buildings and commercial with computers load [6, 7]. The efficient performance of a SAPF mostly based upon three different areas such as estimate the reference source current, current controller, and selection of parameters in SAPF.

To increase the performance of the SAPF researchers have been proposed various extraction technique with numerous current control methods were developed such as Hysteresis, Linear current control, Repetitive, parabolic, Ramp time, current mode, Dead Beat, One cycle, Predictive, Model predictive current control and Artificial intelligence method. The literature explored in this paper involves publications from IEEE, IET, and Elsevier, etc. from 1991 to 2016. This manuscript aims to review and discuss various current control methodologies of single phase SAPF.



2. Review on Current Control Techniques in SAPF

The SAPF system performance mainly depends on the excellence of the applied current control method. The hysteresis and linear current control techniques are mainly used in SAPF filter. The advanced other current control approaches, such as Parabolic Current control, current mode control, Ramp time current control, Delta modulation control, MPCC and artificial intelligence based current control approaches are used to control the single phase SAPF switches

2.1 Hysteresis current controller

From the literature review, it has been noticed that numerous researchers give more importance to the hysteresis controller for SAPF application [8-18]. This method is used to controls inverter switches, it can force the actual current to go up and down to track the input reference current of SAPF. The current error signal $e(t)$, which is the difference between the filter reference current and actual filter current. The Hysteresis current controller is shown in Fig.1a, 1b and Fig. 1c.

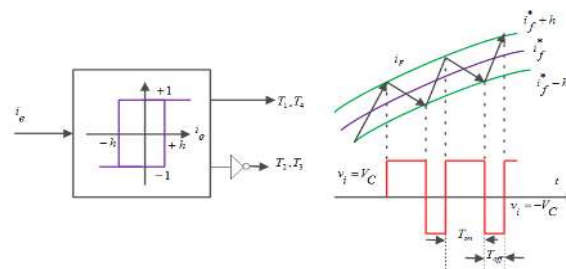


Figure. 1. a. Single band hysteresis current control

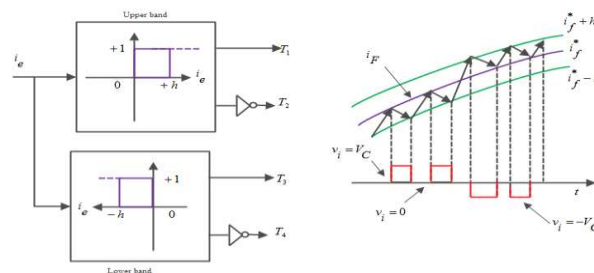


Figure.1. b. Double band hysteresis current control

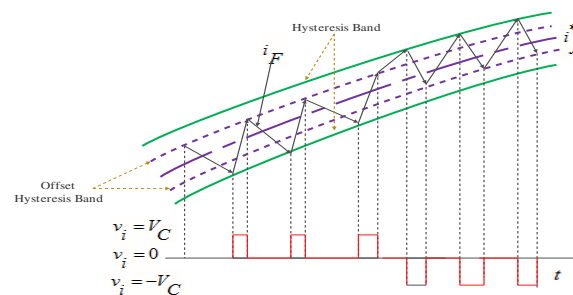


Figure. 1. c three level Hysteresis band

The benefit of the hysteresis control techniques is simple to implement, maximum current limit, high accuracy and fast response in transient condition. The drawbacks of this method are dependent on load

parameters, varying switching frequency with system voltage, generation of sub harmonics which affect the quality power system.

In [29] author proposed the concept of limiting the power devices maximum switching frequency. The calculation of current ripple and the switching frequency by using simple algebraic equation as a function of the hysteresis band, dc bus voltage and inductive output filter value in [30]. The controller has benefits such as simple to implement and fast transient response. Also, it has some problems like mostly operation is dependent on load parameters and switching frequency variations with system voltage.

In [14] the author proposes a new generalized frequency domain formulation based method. It was established based on the Tsytkin's method, the relation between hysteresis bandwidth and the maximum allowable switching frequency of controller were found. The converter switching frequency is mostly based on the converter's parameter, and the load and line of the distribution system.

In [16] the author proposed that a three-level Hysteresis current controller be developed by taking two HCC. By using an extra offset hysteresis band over the exiting two-level based Hysteresis band which have a slight difference in switching frequency as illustrated in Fig 1 (c). In [34] the author introduce a double band based HCC method for SAPF as shown in Fig 1. (b). In this method is to permit access to the zero level of the SAPF input supply voltage due to that an inverter switch is only operated through a half cycle, whereas during another cycle, it remains either on or off. This method gives much lower average switching frequency and low total harmonic distortion when compared with conventional hysteresis based current control for lower hysteresis band values. This method offers better dynamic performance under bridge rectifier with R and RL load conditions.

2.2 Linear Current controller

The active current wave shaping controller to produce the gating signals to the power converter is proposed in [22] [19]. The active current wave shaping controller consisting of a subtraction circuit, an error amplifier, and a PWM modulator. The source current of SAPF is subtracted from the reference source current of SAPF and then sent to an error amplifier if the circuit. The output signal from the error amplifier is fed to the PWM modulator for generation of gating signals. It can be illustrated as

$$V_m(t) = K(i_{s,ref}(t) - i_s(t)) \quad (1)$$

where K is the gain of the error amplifier. In [21] the author proposed modified PWM technique for controlling power converter. The controlling signal is made from the comparison between the source current and its reference. The actual supply current is subtracted from the reference supply current, and then the error current signal is sent to PI controller, it has a limiter circuit at its output side. Subsequently, the controlling signal from the controller is equalled with PWM triangular carrier signal as shown in Fig .2. If the controlling signal output is more than the triangularpwm wave, then the converter upper switching devices are switched on, and also the lower switching devices are switched off, and vice versa. The control signal can be represented in the mathematical model:

$$V_m(t) = K_P (i_{s,ref}(t) - i_s(t)) + \frac{K_I}{s} (i_{s,ref}(t) - i_s(t)) \quad (2)$$

The dynamic response is enhanced by changing the values of K_P and K_I . The PI controller is mainly used for its high DC gain, and to remove the steady state error of the system. The main drawback of this method is bandwidth, which remains unchanged gives delays and substantial error in the following of the high value of harmonics components of the supply reference current. The gain values of the PI controller were found by trial and error method or by optimization method. The modified PWM technique method has the advantage of less THD value when compared to standard PWM.

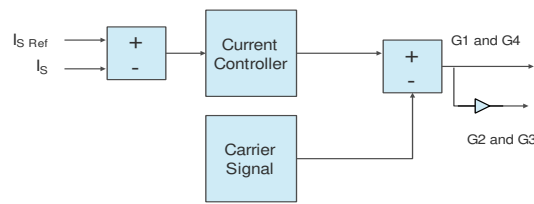


Figure. 2 a PI-PWM Current controller

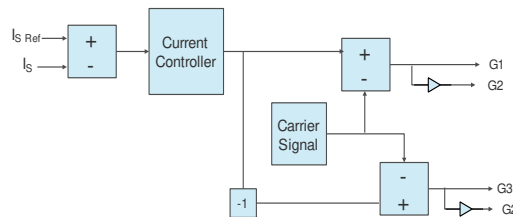


Figure. 2 b PI-M-PWM Current controller

Fig 2 (a) and 2 (b) explains the two different switching techniques for controlling single phase SAPF, which is discussed by the author in [20]. This periodic sampling and Pulse Width Modulation (PWM) for two different switching frequencies are used. This method is simple to implement, but it does not work with a constant switching frequency and PWM method operating with a variable duty cycle and a constant predetermined switching frequency. In this method different types of nonlinear loads were considered to test and analyse the single phase SAPF such as a linear RL load, a controlled bridge rectifier with RL type load, and a same rectifier with RC type load. In rectifier with RL load case source current THD is minimum by using Periodic Sampling method when compared with PWM method. In single-phase, SAPF prototype model with different switching methods was discussed [21].

2.3 Parabolic Current control

The parabolic current control comes under the category of variable hysteresis band current control technique. By using this method to generate the variable hysteresis bands according to the periodic parabolic function to achieve the desired control characteristics with fixed switching frequency and better transient response. The parabolic function is reset when the error signal hits it [22].

2.4 RAMP time current controller

The current controller of the ramp type works so that the current of the inductor accurately tracks the desired reference current with a fixed switching frequency. This technique to generate the gating signal of inverter is based on the instant at which the zero crossing occurs. This control technique is almost continuous and has an excellent dynamic efficiency like a standard hysteresis controller. The input error signal to the PI controller is a binary signal (ϵ), which can point out. The error polarity between the actual and reference compensating reference. And the value of next switching instant is obtained by making use of polarity of error signal and switching of controller. This control technique is designed to generate an accurate control at a moderately small switching frequency band with slight low order harmonics. The ramp type controller is classified into three types

1. Ramp-time current controller
2. Digital-ramp time current controller
3. Polarized Ramp-time current controller

The working concept of Digital Ramp time current controller is discussed in [25]. It is similar to the normal ramp time controller. The main difference between two ramp time control methods is the generation of error polarity signal. Digital Ramp time controller has advantages without using

analogue circuits like ADC, comparator, and DAC to produce ε signal digitally by using internal digital source current by the FPGA controller. By comparing two ramp-time controllers, the normal ramp-time controller is not substantially affected by sampling frequency and it provides better output than the Digital ramp-time controller because of the accuracy of zero crossing of present errors in the analog domain. At the same time, for highly demanding power electronics applications like APF, the digital ramp time controller can be used due to the option of choosing multisampling strategy for its operation. The SAPF can be controlled by the Polarized Ramp-time Current Control (PRCC). It works with a set switching frequency based on the notion of Zero Average Current Error (ZACE), and it does not produce any extra low-order harmonics to the scheme. The PRCC technique has a large bandwidth and a quick transient reaction [26].

2.5 Current-Mode Controller

With a fixed switching frequency, the current mode control technique is used in SAPF. It can be classified as

1. Peak current mode control (Peak CMC)
2. Valley current mode control (Valley CMC).
3. Average current mode control (Average CMC)

In the peak CMC technique, when switching on condition, it senses the inductor maximum current and information is used to turn off the switch. On the other side, it senses the inductor peak current when switching off condition in the Valley CMC technique, and that information is used to turn on the switch. This switching mechanism is called the trailing edge and the leading edge modulation. The Peak CMC method is mostly used in various power converters like rectifiers and converter applications due to it naturally give over current protection. Whereas the valley CMC is used in output current regulators for DC/AC converter and APF, because of its non-average ripple nature, it is unable to deliver the regulated current with zero DC component.

The Peak CMC scheme has drawbacks of a low gain value of current control loop and poor noise immunity. To overcome the above problem, the Average CMC method is used it has high gain value in current control loop, excellent noise immunity and it is tracking the current program with a high degree of accuracy [45].

2.6 Delta Modulation based current control

The delta modulation system is the variation of the standard hysteresis controller, which provides constant voltage during the converter switching period. It operates based on a comparison between fixed tolerance band and current error. When the positive current error occurs during the operation, the inverter output voltage must be positive and the inverter output voltage must be negative if the negative current error occurs. When compared to traditional hysteresis current controller a small phase lag addition in the tracking process is minimized. The main advantage of this method is an excellent dynamic response and simple implementation [24].

2.7 Dead-beat current controller

Since the early 1990s, the dead-beat controller has been used for present inverter control and shunting active filters. This control technique requires detail knowledge of parameters like filter inductance value, line voltage, present active filter current or supply current and the value of reference current. The primary disadvantage of this technique is the delay in the control phase. In order to minimize the harmful delay, a unique technique is implemented to compensate for the mistake of n th and $(n-1)$ th instantly by identifying the error at n th instant with the output at $(n-1)$ th instant. [33]. A modified dead beat controller is used in [34]. By the end of the modulation period , it can estimate the period directly when a switching device is switched on to generate the actual phase current track to its reference. The average value of inverter output voltage can be represented as

$$u_{inv} = \frac{L}{T_s} (i_{ref} - i_{act}) + u_{sys} \quad (3)$$

where u_{inv} is the average value of inverter output, T_s is the sampling time, and u_{sys} is the system voltage. i_{ref}, i_{act} is the reference and actual phase current respectively. It has a simple control algorithm, and it minimizes the number of current sensors and reduces the cost and the size of the system [35-37].

2.8 Model Predictive current controller

Next to previously mentioned current control strategies, there are a few current control techniques are utilized to improve the SAPF execution. A standout amongst the most prominent strategies for current control in SAPF is MPC control method. MPC control technique was developed in the process control sector in 1970, and its interest has only reached its peak in latest days. Its gaining popularity is due to the accessibility of quick processor that in a fraction of seconds can solve many complicated issues. The main benefits of the MPC based control technique are the utilization of variable switching frequency, absence of modulator, lower complexity and the possibility of online optimization for inverters and the addition of constraints. The MPC has recently developed an approach to control of various power converters.

The MPCC of three-Level NPC converter based single phase SAPF is used for compensation of load harmonics [38]. MPCC of single phase SAPF is presented [39]. Photovoltaic integrated SAPF to provide harmonic reactive power compensation using MPC control was given in [40]. This method having better current tracking capability in dynamic conditions. The discrete mathematical of the SAPF, DC Link voltage and equivalent power system impedance are used to design the MPC controller to find out the future reference current. Most of the control methods involve complex calculations, need of modulation stage to produce the switching signals and thus its real-time implementation is time-consuming and challenging. MPC scheme does not require internal current control loops and modulation stage.

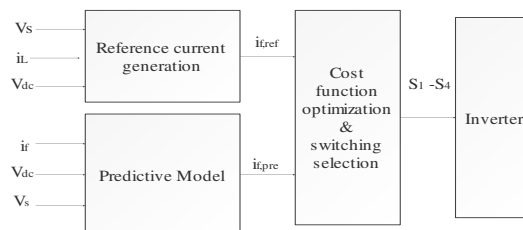


Figure.3. Model Predictive current control schematic diagram

Figure. 3 demonstrates the schematic diagram of a MPC based SAPF. The essential control of MPCC is to limit the error between the references and estimated load current which is characterized as cost function.

To achieve this goal, the SAPF switching state that will reduce 'g' is selected and given at the time of the next sampling instant. The main problem of MPC strategy is variable frequency and involve more design computation. This technique, however, is based on a simple approach and can be easily implemented in real time owing to the rapid growth of controllers such as microprocessors, digital signal processors and field-programmable gate arrays.

In addition, the MPC strategy is flexible ; the controller design includes additional limitations such as minimizing switching frequency and minimizing switching loss. In [42], author mixed predictive control with the traditional space vector modulation system to obtain steady switching frequency operation, but this technique is complicated to implement in real time.

2.9 Intelligent Current Control Techniques

The neural networks belong to the artificial intelligence techniques family, fuzzy logic, genetic algorithms. Artificial Neural network (ANN) is a connection of some artificial neurons which simulate a biological brain system. NN can train either offline or online when it is used in a system control [41]. The ANN based current control of SAPF. The error signal is provided as an ANN input and ANN produces an appropriate switching signal for harmonic and reactive power compensation to the SAPF. In this method, a fixed switching frequency operation is achieved. In this control approach, the conventional controllers are replaced by the fuzzy controller, which possess two input and one output signal. The error (e) and its derivative (de) are used as the input to the fuzzy controller while the output is the command (Cde). The Intelligent Current Control methods do not require a model of SAPF; they need precise knowledge about operation and behavior of SAPF systems.

After reviewing the different current control techniques, we summarized the control methods as shown in Table 1. In the previous sections, current control techniques are studied, and significant advantages and disadvantages were discussed in Table 1. This table gives a better idea to the researcher to select the optimal controller for designing a SAPF. By exploring different current controllers due to their dynamic performance, tracking behavior and switching frequency, it is concluded that MPC control is a better choice for APF applications. The drawback of MPC controller is that switching frequency variations. To solve this problem the combined predictive control with traditional space vector modulation scheme to prefer or to achieve constant switching frequency operation optimized MPC controller is used.

Table 1. Comparison of current controller

Type of Current Controller	Advantages	Disadvantages
Hysteresis Controller	<ul style="list-style-type: none"> • Simple and Robust • Fast transient response • Doesn't need complex circuits for real-time implementation • High robustness 	<ul style="list-style-type: none"> • Variable switching frequency • High current ripple • Not preferable in lower power level applications due to switching loss.
PI-PWM Controller	<ul style="list-style-type: none"> • Fixed switching frequency • Small calculation time • Simple to implement 	<ul style="list-style-type: none"> • Accurate tuning is needed • Non zero steady-state error • Poor dynamic response
Parabolic Current control	<ul style="list-style-type: none"> • Fast transient response • High accuracy control with constant frequency switching 	<ul style="list-style-type: none"> • Due effect of dead time the stable duty cycle is reduced, switching frequency deviation occur and current tracking error increased. • Inadequate resolution of parabolic carrier generators could influence the current control performance. • Noise from the control board influences the control accuracy

Ramp time current controller	<ul style="list-style-type: none"> • Fixed frequency switching • Good performance dynamic 	<ul style="list-style-type: none"> • Relatively complex
Current-Mode Controller	<ul style="list-style-type: none"> • Fixed frequency switching 	<ul style="list-style-type: none"> • It is mostly not preferable in VSI application due presence of significant DC component in the current
Delta Modulation based current control	<ul style="list-style-type: none"> • Easy implementation • Simple control process due to inherent self-carrier generating feature 	<ul style="list-style-type: none"> • Asymmetrical operation
Dead-beat current control	<ul style="list-style-type: none"> • Fixed frequency switching • High performance dynamic • Digital in nature 	<ul style="list-style-type: none"> • Low robustness • High computational power • Relatively complex
Model Predictive Control	<ul style="list-style-type: none"> • Possibility to include nonlinearities • High dynamic response • Allow attaining more accurate current control with less harmonic distortion • System perturbations and dead times can be compensated 	<ul style="list-style-type: none"> • Variable switching frequency • Needs many calculations • Selection of weighting factor is not analytical or numerical
Intelligent Current Control	<ul style="list-style-type: none"> • Fixed frequency switching operation 	<ul style="list-style-type: none"> • Need precise knowledge about operation and behavior of SAPF systems

3. Conclusion

In this manuscript, a classification and comparison of different SAPF control techniques were evaluated. In addition, the present control technique proposed and used by different researchers is up to date and has been recognized and summarized with its pros and cons. The comparisons table is showed to discuss the various current controllers in detail. From the review, the authors discovered that predictive current controllers have a wide range of developments in recent days, which may give better and more efficient results than the existing controllers. It is envisaged that this manuscript will be a suitable one-stop reference source for engineers, manufacturers, and researchers involved in the topic discussed.

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