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A Novel SRF Based Cascaded Multilevel Active Filter for Power Line Conditioners

Karuppanan P and Kamalakanta Mahapatra

Department of Electronics and Communication Engineering,
National Institute of Technology, Rourkela, India-769008
karuppanan1982@yahoo.co.in and kkm@nitrkl.ac.in

***Abstract*— This paper presents a novel synchronous reference frame (SRF) controlled five-level cascaded multilevel inverter based shunt active filter for power line conditioners (PLCs) to improve the power quality in the distribution system. The SRF based compensation is developed by sensing load currents only, which require for harmonics and reactive power compensation due to non-linear loads. The attempt is to come up with a simple control strategy. Incidentally it is different from conventional methods and provides superior performance. The cascaded multilevel voltage source inverter switching signals are generated from proposed triangular-periodical current controller; that gives better dynamic performance under transient and steady state conditions. The proportional integral (PI) controller is used to maintain the capacitance voltage of the cascaded inverter almost constant. The extensive simulation results demonstrate that the cascaded multilevel inverter based active power filter using the synchronous reference frame controller effetely compensates the current harmonics and reactive volt amperes under both steady state and transient conditions.**

***Keywords* — Synchronous reference frame (SRF) controller, active power line conditioners (APLC), Triangular-periodical current controller, Harmonics, Power quality**

I. Introduction

Nonlinear loads such as diode/thyristor rectifiers, switched mode power supply (SMPS), welding equipment, incandescent lighting, and motor drives are degrading power quality in transmission and distribution grid systems. These non-linear loads result in harmonic or distortion current and create reactive power problems [1]. These harmonics induce malfunctions in sensitive equipment, overvoltage by resonance, increased heating in the conductors and harmonic voltage drop across the network impedance that affects power factor [2]. Traditionally passive filters have been used to compensate harmonics and reactive power; but passive filters are large in size; aging and tuning problems exist and can resonate with the supply impedance. Recently active power line conditioners (APLC) or active power filters (APF) are designed for compensating the current-harmonics and reactive power simultaneously [3].

The controller is the most significant part of the APF topology and extensive research is being conducted to improve its control strategy. In 1979, FBD (Fryze-Buchholz-Dpenbrock) method is used in time domain and real time for compensating current harmonics [4]. In 1984, H.Akagi [5] introduced instantaneous active and reactive power theory method that is quite efficient for balanced three-phase loads, being later worked by Watanabe and Aredes [6] for three-phase four wires power systems, zero-sequence currents was later proposed by F.Z.Peng [7]. In 1995, Bhattacharya proposed the calculation of the d-q components of the instantaneous three-phase currents and this method creates a synchronous reference frame concept [8]. The SRF method is consists of a phase locked loop (PLL) circuit and abc-dqo transformation; it is a simple algorithm and good dynamic responses. The SRF is ability to compensate harmonics and reactive-power component from the distortion load currents [9-11].

This paper present a novel synchronous reference frame controller based cascaded shunt active power filter for the harmonics and reactive power mitigation of the non-linear loads. The cascaded H-bridge active filter has been applied for power quality applications due to increase the number of voltage levels, low switching losses and higher order of harmonic elimination. The cascade M-level inverter consists of (M-1)/2 H-bridges and each bridge has its own separate dc source [1-2] [11]. The cascaded voltage source inverter switching signals are generated using proposed triangular-periodical current controller; it provides better dynamic performance under both transient and steady state conditions. The compensation process is based sensing load currents only, which require current harmonics and reactive power elimination due to the loads. The PI-controller is used to maintain the capacitance voltage of the cascaded inverter constant. The shunt APLC system is validated through extensive simulation and investigated under steady state and transient with different non-linear loads.

II. Design of shunt APLC system

Cascaded active filter for power line conditioning system is connected in the distribution network at the PCC through filter inductances and operates in a closed loop. Three phase active power filter comprises of 24-power transistors with freewheeling diodes; each phase consists of two-H-bridges in cascaded connection and every H-bridge having a dc capacitor. The shunt APLC system contains a cascaded multilevel inverter, RL-filters, a compensation controller (synchronous reference frame controller) and switching signal generator (triangular-periodical current controller) as shown in the Fig 1.

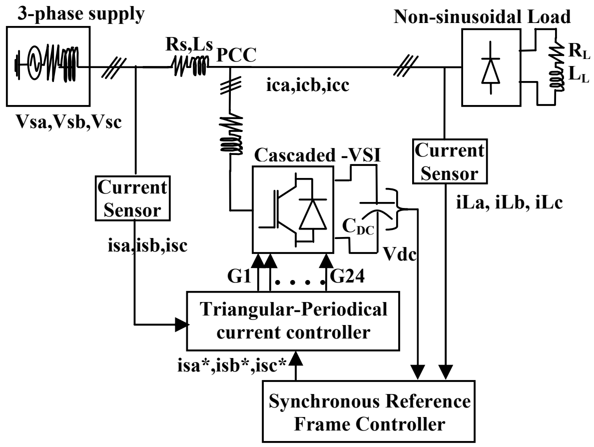

Fig 1 shunt active power line conditioners system

Three phase supply source connected with the non-linear load. The nonlinear load current should contain fundamental component and harmonic current components. For harmonic compensation, the active filter must provide the compensation current $i_c(t) = i_L(t) - i_s(t)$. At that time, source current will be in phase with the utility voltage and become sinusoidal.

Power Converter:

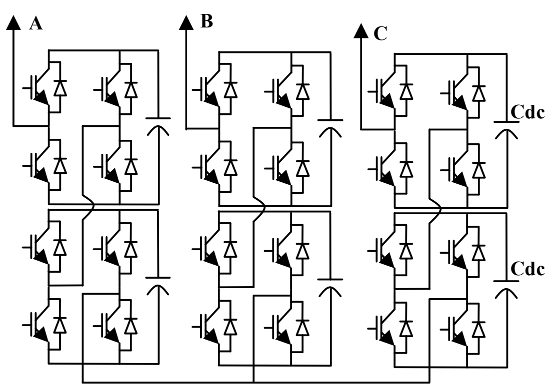

Fig 2 Design of cascaded multilevel active power filter

A cascaded multilevel active power inverter is constructed by conventional of H-bridges. The three-phase active filter comprises of 24-power transistors and each phase consists of two-H-bridges in cascaded method for 5-level output voltage, shown in Fig 2. Each H-bridge is connected a separate dc capacitor and it serves as an energy storage elements to supply a real power difference between load and source during the transient period. The capacitor voltage is maintained constant using PI-controller and the output voltage is Vdc . The 24-power transistors switching operations are performed using proposed triangular-periodical current controller and harmonics is achieved by injecting equal but opposite current harmonic components at point of common coupling (PCC).

III. PROPOSED CONTROL STRATEGIES

The proposed control system consists of reference current control strategy using SRF method and triangular-periodical current modulator for switching signals of cascaded VSI.

A) SRF Control strategy:

The synchronous reference frame theory is developed in time-domain based reference current generation techniques. The SRF is performing the operation in steady-state or transient state as well as for generic voltage and current; it's capable of controlling the active power filters in real-time system. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The block diagram of the synchronous reference frame controller is shown in Fig 3.

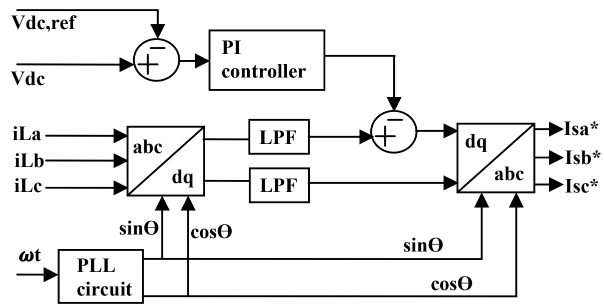

Fig 3 Synchronous reference frame controller

The basic structure of SRF methods consists of direct (d-q) and inverse $(d\text{-}q)^{-1}$ park transformations, which allow the evaluation of a specific harmonic component of the input signals. The reference frame transformation is formulated from a three-phase $a - b - c$ stationery system to the two-phase direct axis (d) – quadratic axis (q) rotating coordinate system. In a-b-c stationary axes are fixed on the same plane and separated from each other by 120^o. These three phase space vectors stationary coordinates are easily transformed into two axis d-q rotating reference frame. This proposed algorithm derivate from a three-phase stationary coordinate load current i_{La}, i_{Lb}, i_{Lc} are convert to i_d-i_q rotating coordinate current, as follows

$$i_d = \frac{2}{3}\left[i_{La}\sin(\omega t) + i_{Lb}\sin(\omega t - \frac{2\pi}{3}) + (i_{Lc}\sin(\omega t + \frac{2\pi}{3}) \right] \quad (1)$$

$$i_q = \frac{2}{3}\left[i_{La}\cos(\omega t) + i_{Lb}\cos(\omega t - \frac{2\pi}{3}) + (i_{Lc}\cos(\omega t + \frac{2\pi}{3}) \right] \quad (2)$$

The d-q transformation output signals depend on the load currents (fundamental and harmonic frequency components) and the performance of the phase locked loop. The PLL circuit of rotation speed (rad/sec) of the rotating reference frame ωt set as fundamental frequency component. The PLL circuit is providing sinΘ and cosΘ for synchronization. The id-iq current passed through low pass filter (LPF) for filtered the harmonic components and allows only the fundamental frequency components. The LPF design is based on Butterworth method and the filter order is 2. The band edge frequency is selected the fundamental of 50 Hz for eliminate the higher order harmonic components. Proportional Integral (PI) controller is used to eliminate the steady state error of the DC-component of the cascaded multilevel inverter and maintains the dc-side capacitor voltage constant. The dc capacitor voltage is sensed and compared with reference voltage for calculate the error voltage. These error voltage involved the P-I gain (K_P=0.1 and K_I=1) for regulate the capacitance voltage in the dynamic conditions. In accordance to the PI controller output is subtracted from the direct axis (d-axis) of harmonic component for eliminate the steady state error. The algorithm is further developed to the desired reference current signals in d-q rotating frame is converted back into $a-b-c$ stationery frame. The inverse transformation from $d-q$ rotating frame to $a-b-c$ stationery frame is achieved by the following equations

$$i_{sa}^* = i_d \sin(\omega t) + i_q \cos(\omega t) \quad (3)$$

$$i_{sb}^* = i_d \sin(\omega t - 2\pi/3) + i_q \cos(\omega t - 2\pi/3) \quad (4)$$

$$i_{sc}^* = i_d \sin(\omega t + 2\pi/3) + i_q \cos(\omega t + 2\pi/3) \quad (5)$$

The reference frame is rotates synchronous with fundamental currents. Therefore, time variant currents with fundamental frequencies would be constant after transformation. Thus, currents would be separated to DC and AC components. AC components of d-axis and in q-axis current are used for harmonics elimination and reactive power compensation.

B) Proposed triangular-periodical current modulator:

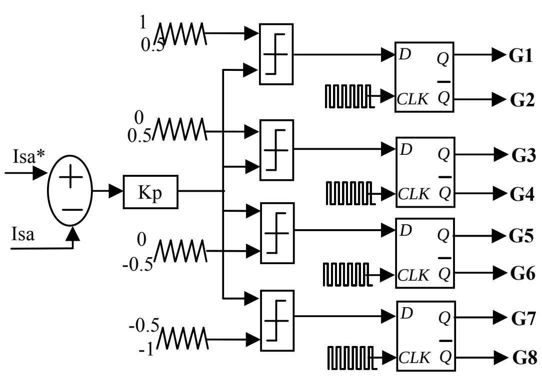

Fig 4 Proposed triangular-periodical current controller

The proposed triangular-periodical current modulator for APF line currents can be executed to generate the switching pattern of the cascaded voltage source inverter. There are various current control methods proposed; but the triangular-periodical current control method has the highest rate for cascaded active power filters. These inverters features are quick current controllability, the switching operation induced the suppression of the harmonics and the average switching frequency of each inverter is equality. The five-level voltage source inverter systems of the current controller are utilized independently for each phase. Each current controller directly generates the switching signal of the three A, B, C phases. The A-phase actual source current represented as isa and reference current represent as isa* as shown in Fig 4, similarly derived the B and C phase currents. To determine the switching frequency by means the error current [desired reference current compared with the actual source current] multiplied the proportional gain (Kp) and compared with triangular-periodical signal. The four triangular signals are generated same frequency with different amplitude for cascaded inverter. Thus the switching frequency of the power transistor is equal to the frequency of the triangular-periodical signal. Then, the output signal of the comparator is sampled and held D-Latch at a regular interval *Ts* synchronized with the clock of frequency equal to $1/Ts$. Note that 4-external clock applied to 1-phase converter and Ts is set as 30 ns, because each phase in one converter does not overlap other phase. Therefore the harmonic currents are reduced as if the switching frequency were increased. The active filter suppresses the harmonics caused by the switching operation of the cascaded inverter.

IV. Simulation Result and Analysis

The performance of the proposed SRF controller based cascaded active filter is evaluated through Matlab/Similink power tools. The system parameters values are; Line to line source voltage is 440 V; System frequency (f) is 50 Hz; Source impedance of L_S is 1 mH; Filter impedance of R_c, L_c is 0.1 Ω; 1 mH; diode rectifier R_L, L_L load: 20 Ω; 100 mH; DC side capacitance (C_{DC}) is 2100 µF; Reference voltage ($V_{DC, ref}$) is 150 V; Power devices are IGBTs with freewheeling diodes. The simulation result of the rectifier load current or source current before compensation is shown in Fig 5 (a). The reference fundamental current is extracted from the loads using the proposed SRF controller that is shown in Fig 5(b).

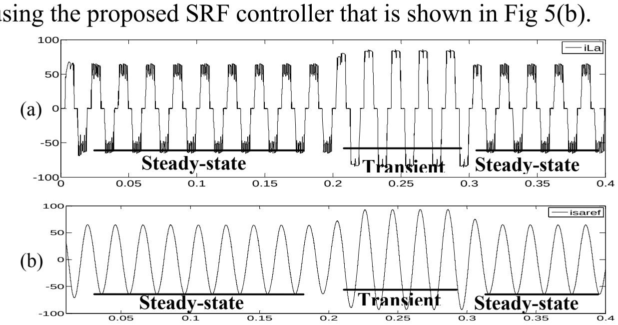

Fig 5 Simulation results for SRF controller based cascaded APF (a) source currents before compensation or load current (b) extracted reference current.

The active filter must provide the harmonic filter current or compensation current as $i_c(t) = i_L(t) - i_s(t)$, shown in Fig 6(a). The simulation of source current after compensation is shown in Fig 6(b) that indicates the current is sinusoidal. We have additionally achieved power factor correction as shown in Fig 6(c) that result indicate a-phase voltage is in- phase with a-phase current. The DC-side capacitors voltage is controlled by PI-controller that is shown in Fig 6 (d). It serves as an energy storage element to supply a power to operate three-phase cascaded multilevel inverter. These figures are focused in A-phase only other phases is just phase shifted by 120^0

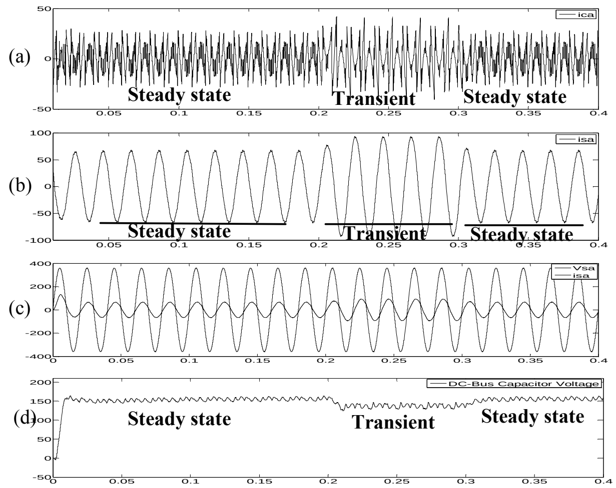

Fig 6 SRF based cascaded APF Simulations (a) Compensation current (b) Source current after active filter (c) power factor correction (d) DC-side capacitor voltage

The Fast Fourier Transform (FFT) is used to measures the order of harmonics with the fundamental frequency at 50 Hz for the source current that is shown in Fig 7.

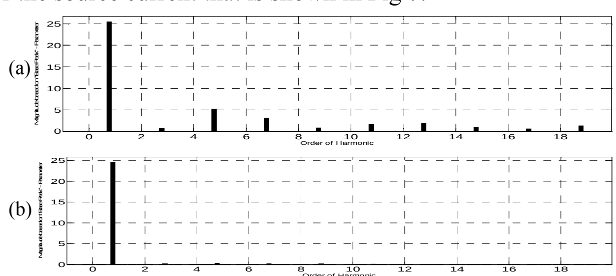

Fig 7 SRF based cascaded APF; Order of harmonics (a) the source current without active filter (THD=28.94%), (b) with active filter(THD=2.17%)

The total harmonic distortion (THD) measured at the source (current) on the distribution system and the various parameters measured without APF and with APF are presented in Table 1

Table 1 various parameters measured without APF and with APF

Parameters	Source Current(I_S) without APF	Source Current(I_S) with APF
THD	28.94 %	2.17 %
Real Power (P)	9.15 kW	10.41 kW
Reactive volt Ampere Power (Q)	490 VAR	315 VAR
Power factor	0.8793	0.9838

The SRF based cascaded active filter simulation is done with various non-linear load conditions. FFT analysis indicates that the active filter brings the THD of the source current to 2.17 % that is less than 5% which is in compliance with IEEE 519-1992 and IEC 61000-3 standards for harmonics under non-linear and/or unbalanced load conditions.

V. CONCLUSIONS

This paper indicates the suitability of cascade multilevel inverter based active filter for power line conditioning of distribution networks. The cascaded inverter provides lower cost, higher performance and higher efficiency than the traditional PWM-inverter for power line conditioning applications. The cascaded inverter switching signals are derived from the proposed triangular-periodical current modulator that provides good dynamic performance under both transient and steady state operating conditions. SRF is employed to extract the fundamental component from the non-linear load currents. This controller is developed by sensing load currents only. This approach is fairly simple to implement and is different from conventional methods. The PI-controller maintains the capacitance voltage of the cascaded inverter nearly constant. The extensive simulation results demonstrate the performance of the APF under different non-linear load conditions.

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