

# Closed Loop Control of Multilevel Shunt Active Filter with BLDC Motor Drive

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**ABSTRACT:** Active filters provide a viable solution to reduce harmonics caused by diode or thyristor rectifier front-ends in high power variable speed motor drives. Compared with the series and hybrid filter configurations, the shunt active filters do not need extra coupling transformer and requires less protection and switchgear. To handle the large compensation currents and provide better thermal management, two or more parallel connected semiconductor switching devices can be used. This paper presents a shunt active filter configuration that uses tapped reactors for harmonic current sharing. It also reduces voltage stress across the switches by utilizing a conventional three-level flying capacitor topology. A current balancing algorithm is proposed to keep the reactor magnetizing current to a minimum. Overall the configuration is capable of producing nine distinct voltage levels and thus reduces switching ripple in the compensating currents. The proposed topology is implemented to BLDC Motor Drive. The results of the proposed system was obtained through Matlab/Simulink software. It is shown through simulation the proposed active filter can achieve high overall system performance.

**KEYWORDS:** Shunt active filter, Total Harmonic distortion, BLDC motor.

## I. INTRODUCTION

Variable speed motor drives have found extensive application in a variety of high-power and high voltage systems. One example is the electric propulsion system used in modern naval ships, the power ratings of which can be tens of megawatts. Typically the front-ends of such adjustable speed drives employ a diode or thyristor rectifier. In spite of their simple control and robust operation, these devices can result in serious power quality problems. They can generate voltage and current harmonics that might affect the operation of other devices in the same ac system. Conventionally, *L-C filters* are used to reduce harmonic related issues. However, due to their large size and inflexibility, passive filters are gradually being replaced by active filters that utilize power electronic inverters to provide compensation for harmonics. Among various active filter topologies, the shunt active filter have a number of advantages and constitute the optimal harmonic filtering solution for variable speed drive rectifier front-ends. The shunt active filters do not need an additional coupling transformer and require much less protection and switch-gear. They operate as three-phase controlled harmonic current sources and are not affected by harmonic distortions in supply voltages. For high-power applications such as ship propulsion systems, the large compensation current often requires parallel operation of two or more switching devices.

In recent years, multilevel converters have shown some significant advantages over traditional two-level converters, especially for high power applications. In addition to their superior output voltage quality, they can also reduce voltage stress across switches. Since the output voltages have multiple levels, lower  $dv/dt$  is achieved, which greatly alleviates electromagnetic interference problems due to high frequency switching. Over the years most research work has focused on converters with three to five voltage levels, although topologies with very high number of voltage levels were also proposed. In general, the more voltage levels a converter has the less harmonic and better power quality it provides. However, the increase in converter complexity and number of switching devices is a major concern for multilevel converter. It has been shown that although more voltage levels generally mean lower total harmonic distortion (THD), the gain in THD is marginal for converters with more than seven levels. Recently, the small and medium size motor industries are developing rapidly because of its simple and small structure. The BLDC motor has the advantages of high efficiency, long lifetime, better speed torque characteristics and high torque to weight ratio compared to DC motor, Induction motor and Switched Reluctance motor. It is used in the field of electric drives, aerospace engineering, robotics etc.

This paper presents a shunt active filter configuration that uses tapped reactors for harmonic current sharing. It reduces current stress of the switching devices by distributing the compensation current between two parallel legs of a H-bridge

topology. It also reduces voltage stress across the switches by utilizing a conventional three-level flying capacitor topology. Overall, the configuration is capable of producing nine distinct voltage levels and thus greatly reduces switching ripples in the compensating currents. Finally the proposed topology is implemented to BLDC Motor Drive to check the performance of the system.

## II. ACTIVE FILTER INTERFACE

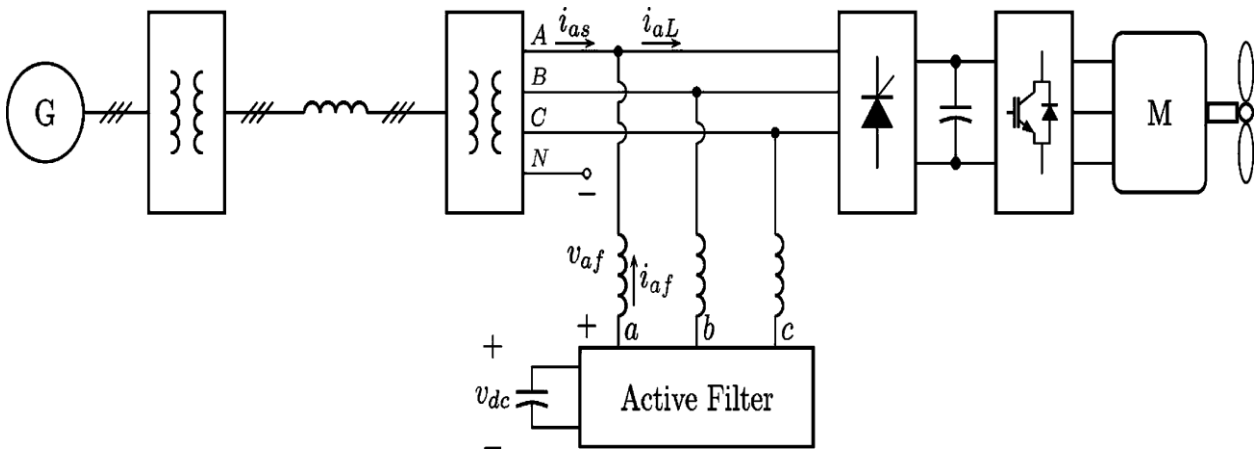


Fig. 1 Active filter topology

As shown in Fig. 1, the active filter is connected to the power system via a three phase inductor  $L_f$ . The filtering function is achieved by injecting a compensating harmonic current into the point of common coupling of the utilityload interface, which in this case is the secondary side of the rectifier load transformer. The reference harmonic currents are extracted from the load currents so that the sum of the load currents and the injection currents has a THD that meets required specifications. The nine-level inverter can produce an output voltage that contains much less switching frequency ripple than a conventional two level inverter. Thus, the generated injection currents are smoother and the coupling inductor can be reduced. According to the inverter equations, the line-to-neutral voltage  $v_{af}$  depicted in Fig. 1. can be related to the inverter line to ground voltages by

$$V_{af} = \frac{2}{3}V_{ag} - \frac{1}{3}V_{bg} - \frac{1}{3}V_{cg}$$

## III. ACTIVE FILTER CONTROL

To effectively compensate the load harmonic currents, the active filter controller should be designed to meet the following three goals: 1) Extract and inject load harmonic currents; 2) Maintain a constant dc capacitor voltage; 3) Avoid generating or absorbing reactive power with fundamental frequency components.

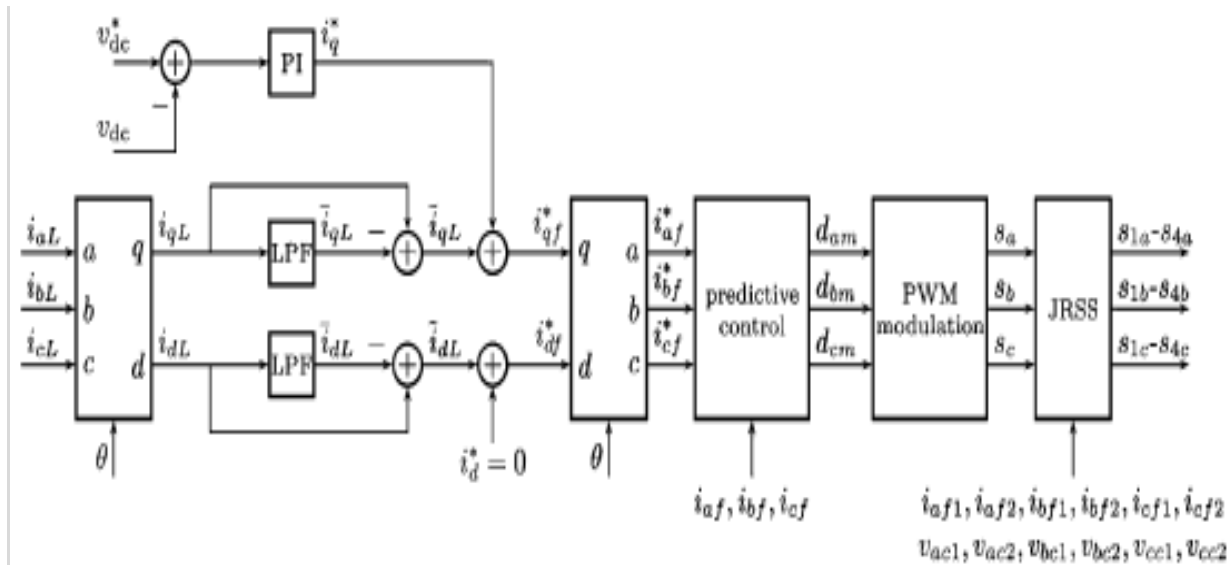


Fig. 2 Active filter control

#### IV. HARMONIC CURRENT EXTRACTION

For diode or thyristor rectifier loads, the most common harmonic currents are of the 5th, 7th, 11th, and 13th order. Although a high-pass filter can be used to extract these components directly, from the line currents, it is not feasible to obtain high attenuation at the fundamental frequency due to the high current amplitude. The synchronous  $q-d$  reference frame controller developed for shunt active filter systems is used to generate the reference compensating current. As shown in Fig. 2 the measured load phase currents ( $i_{aL}$ ,  $i_{bL}$ , and  $i_{cL}$ ) are first transformed into the synchronous reference frame to obtain  $i_{qL}$  and  $i_{dL}$ . The synchronous reference frame phase angle can be obtained by processing the measured system voltage with a phase-locked loop circuit or algorithm. Low-pass filters are then used to extract the dc components, which correspond to the fundamental frequency components of the load currents. The dc component is removed by a simple subtraction of the filtered components ( $i_{qL}$ ,  $i_{dL}$ ) and the transformed components ( $i_{qL}$ ,  $i_{dL}$ ).

#### V. DC CAPACITOR VOLTAGE CONTROL

For the active filter to operate effectively, it is important to maintain the dc capacitor voltage at a constant value. Since the active filter topology is essentially identical to that of an active rectifier, similar control strategies for the active rectifier are applicable. The dc capacitor voltage is directly affected by the real power transferred across the active filter. To keep the voltage constant, ideally, no real power should be transferred. However, due to losses in switching devices and other components, a small amount of real power is needed. In the synchronous reference frame with the  $q$ -axis aligned with the voltage at the point of common coupling, the real power transferred can be expressed as

$$P = \frac{3}{2} V_{qs} i_{qf}$$

This means that by adjusting the  $q$ -axis filter current, the real power can be effectively controlled. The capacitor voltage regulation is then handled by a simple proportional-integral (PI) control adding to the  $q$ -axis filter current.

#### VI. REACTIVE POWER CONTROL

In most cases, a unity power factor for fundamental frequency components is required at the active filter terminals. Since the reactive power can be expressed as

$$Q = \frac{3}{2} V_{qs} i_{df}$$

It can be achieved by keeping the average  $d$ -axis current at zero. The combined control of dc capacitor voltage and reactive power uniquely determines the fundamental frequency component of the active filter output current. This current is then superimposed onto the commanded harmonic currents, and the commanded filter currents  $i_{af}^*$ ,  $i_{bf}^*$ , and  $i_{cf}^*$  are obtained by the reverse transformation.



**VII. HARMONIC CURRENT REGULATOR**

A current regulator is needed to generate the commanded Compensation current. Generally, a hysteresis control provides fast response and is suitable for non sinusoidal current tracking. However, it suffers from some serious disadvantages such as variable switching frequency and phase interaction problems. In addition, to fully take advantage of the benefits of a multilevel converter, a current regulator that uses a voltage source Pulse width modulation (PWM) is desirable. Several frequency-selective harmonic current regulators were proposed in that to achieve zero steady-state error for the dominant harmonics. They all have to target specific frequencies and require a significant amount of computation time. In this paper, a predictive current regulator is implemented to track the harmonic currents, which has the advantages of simple structure and less computational requirement. Given the measured system voltages and filter inductor currents, the required phase a filter voltage can be calculated based on the known value of the filter inductance

$$v_{af}^* = \hat{v}_{as} + \frac{(\hat{i}_{af}^* - i_{af})L_f}{\Delta t}$$

Where  $\Delta t$  is the controller switching period,  $V_{as}$  is the predicted source voltage and can be calculated through linear extrapolation

$\hat{i}_{af}^*$  is the predicted reference harmonic current

$$\hat{v}_{as} = v_{as}(t) + 1.5\Delta t [v_{as}(t) - v_{as}(t - \Delta t)]$$

$$\hat{i}_{af}^* = i_{af}^*(t) + 2\Delta t [i_{af}^*(t) - i_{af}^*(t - \Delta t)].$$

For accurate current tracking, the prediction takes into account the controller delay due to data acquisition and calculation. Better performance has been achieved when a second-order prediction method is used. As can be seen, the predictive control effectively turns the commanded currents into commanded voltages suitable for a voltage-source modulator. These commanded voltages are then expressed as PWM duty cycles by normalizing them to the dc voltage and giving them an appropriate range. For phase a, the duty cycle can be expressed as

$$d_{am} = \left( \frac{v_{af}^*}{v_{dc}} + 0.5 \right) (n - 1)$$

Where n is the number of voltage levels, which for this topology is n = 9. Similar expressions can be written for phase b and phase c. The predictive control have outputs to the PWM modulator.

**VIII. CAPACITOR VOLTAGE BALANCING**

After carrying out the modulation, the switching states for each phase need to be broken out into transistor signals. In order to have the correct voltage levels, the flying capacitors must remain charged at exactly vdc/2. This can easily be assured using the redundancy of the inverter legs.

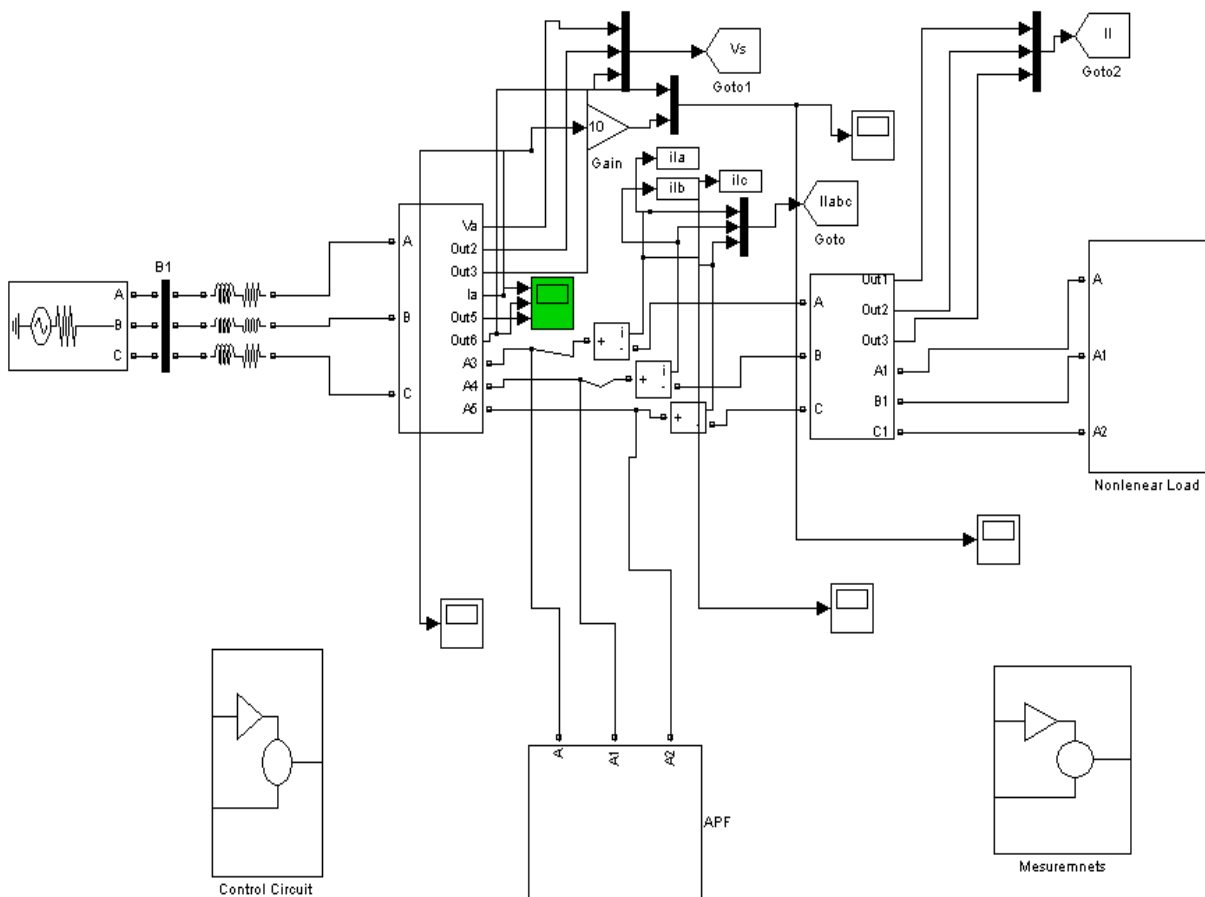
Table 1 Flying capacitor voltage balancing

$s_{1a}$	$s_{2a}$	$v_{a1}$	$i_{af1}$	Charging
0	0	0	+	0
0	0	0	-	0
1	1	$v_{dc}$	+	0
1	1	$v_{dc}$	+	0
0	1	$v_{dc}/2$	+	-
0	1	$v_{dc}/2$	-	+
1	0	$v_{dc}/2$	+	+
1	0	$v_{dc}/2$	-	-

For each leg of the H-bridge structure, there are four switches and a total of four switching states. Two of the switching states can produce the same  $v_{dc}/2$  output, which provides great flexibility for capacitor charging and discharging. Table 1 shows the relationship between switching states, output current direction, and capacitor charging/discharging, where the left leg of phase  $a$  bridge is used as an example. The + and - signs for the output current denote the polarity of the current. The charging status of the flying capacitor can be + (charging), - (discharging), or 0 (neither charging nor discharging). It can be seen that for state  $(s1a, s2a) = (0, 0)$  and  $(1, 1)$ , output current does not flow through the flying capacitor, so the capacitor voltage does not change. The two redundant states  $(1, 0)$  and  $(0, 1)$  produce the same output voltage  $v_{dc}/2$ . Both can be used to charge or discharge the capacitor, depending on the direction of output current.

### IX. SIMULATION RESULTS

The Fig.3 shows the simlink model of closed loop control of shunt active filter with BLDC motor drive. It consists of three phase sinusoidal source voltage block, nonlinear diode bridge load block, BLDC drive block. Since the load is non linear it will draw harmonic currents from source.



. Fig. 3 Closed Loop control of APF with BLDC motor drive

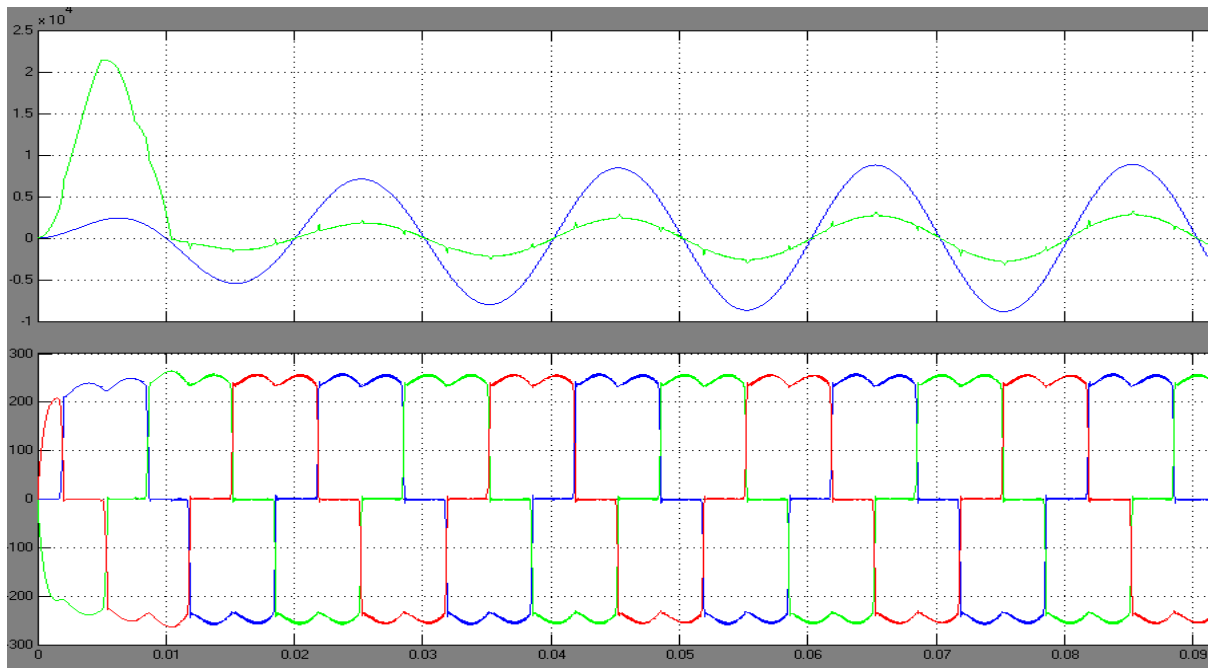


Fig. 4 Sinusoidal source current and three phase Non Sinusoidal load current

From the Fig. 4 it is clear that load current is non linear due to non linear load. THD of source current is 4.88%.

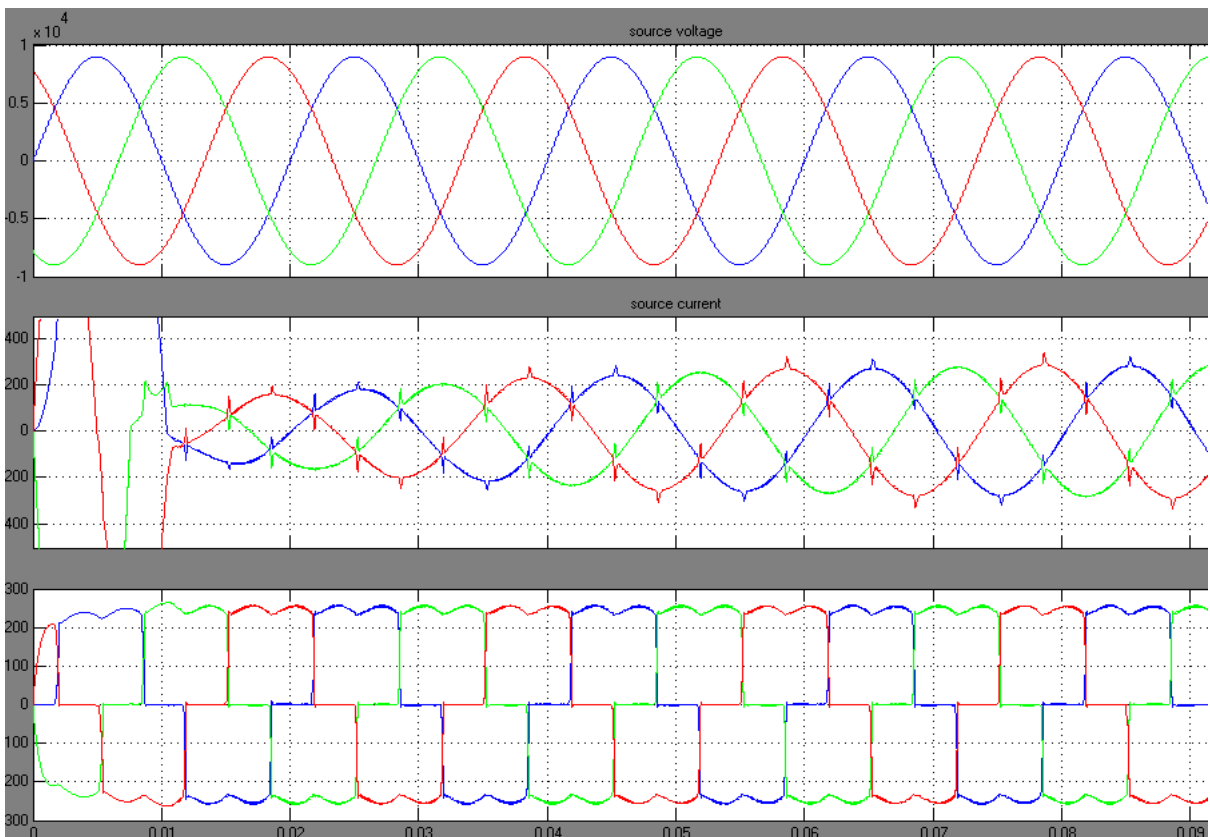


Fig. 5 Source voltage and Source current and Load Current

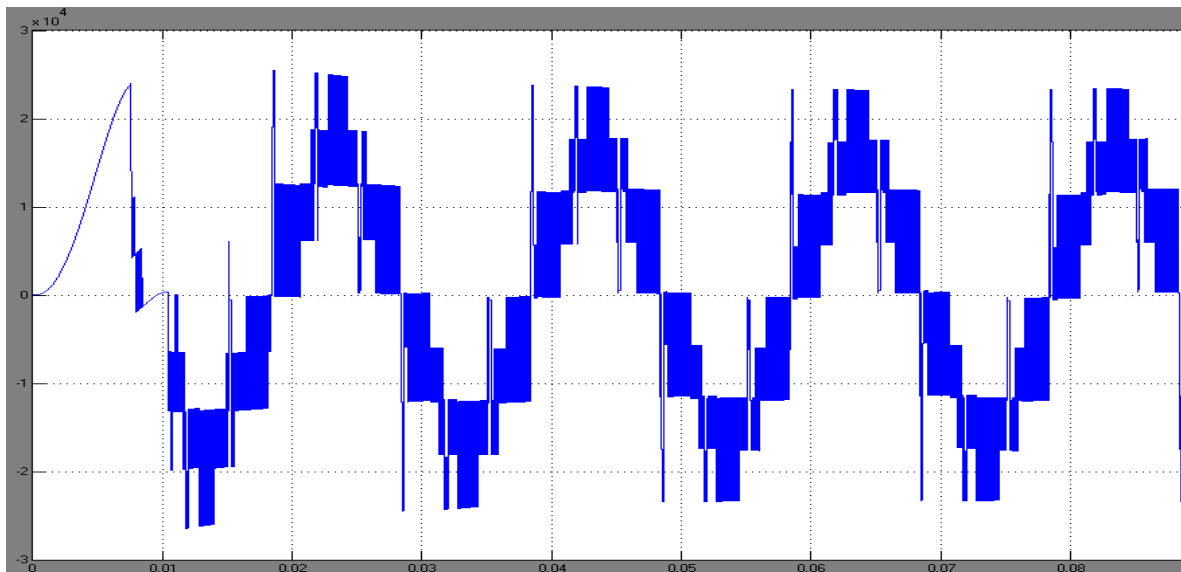


Fig. 6 APF output voltage

Fig. 6 shows the nine levels APF output. Here the distortions are high frequency distortions due to series inductance of converter.

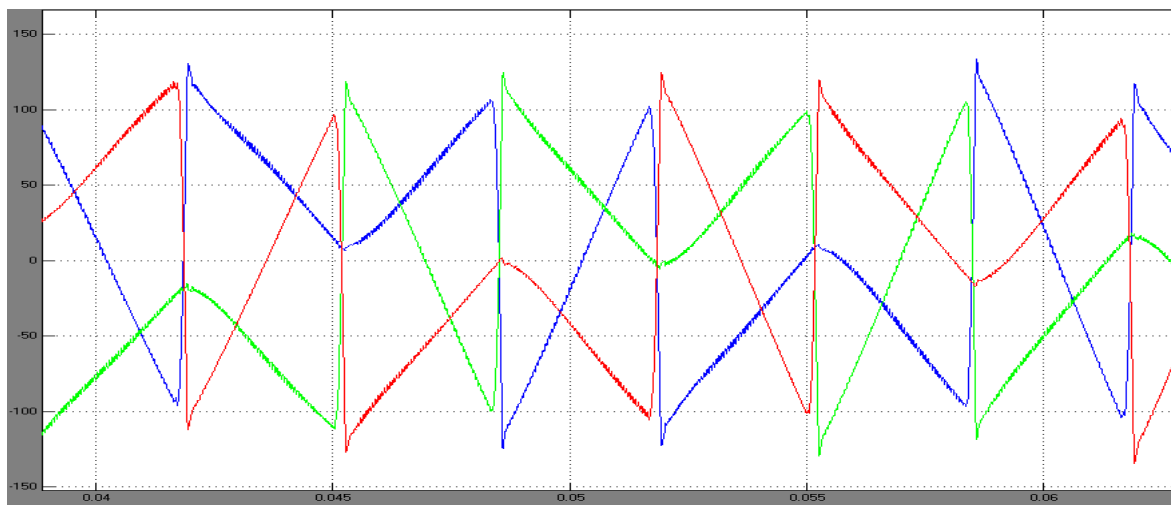


Fig.7 Compensation currents

Fig.7 shows the APF compensation currents. It is clear that APF currents are non sinusoidal to make source current sinusoidal.

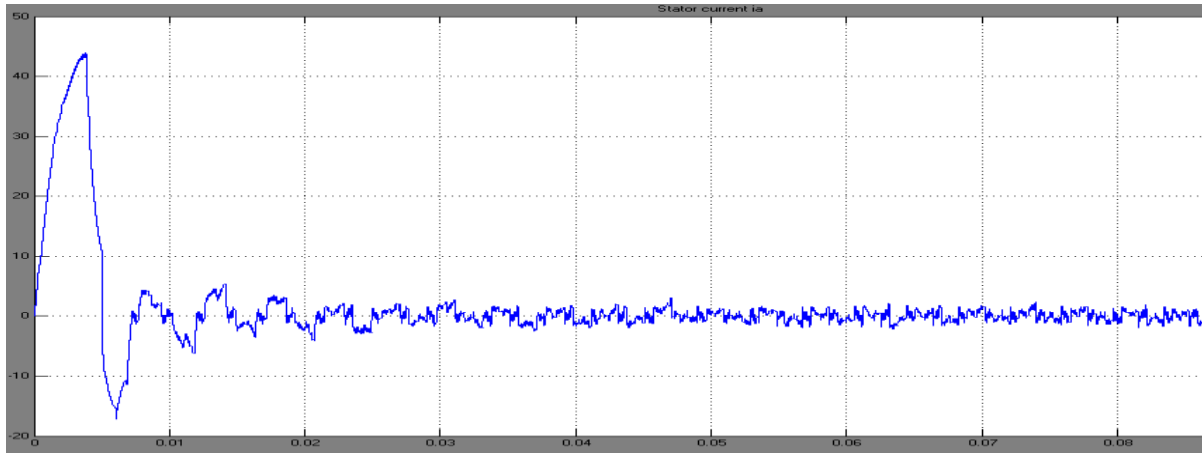


Fig. 8 BLDC current wave form

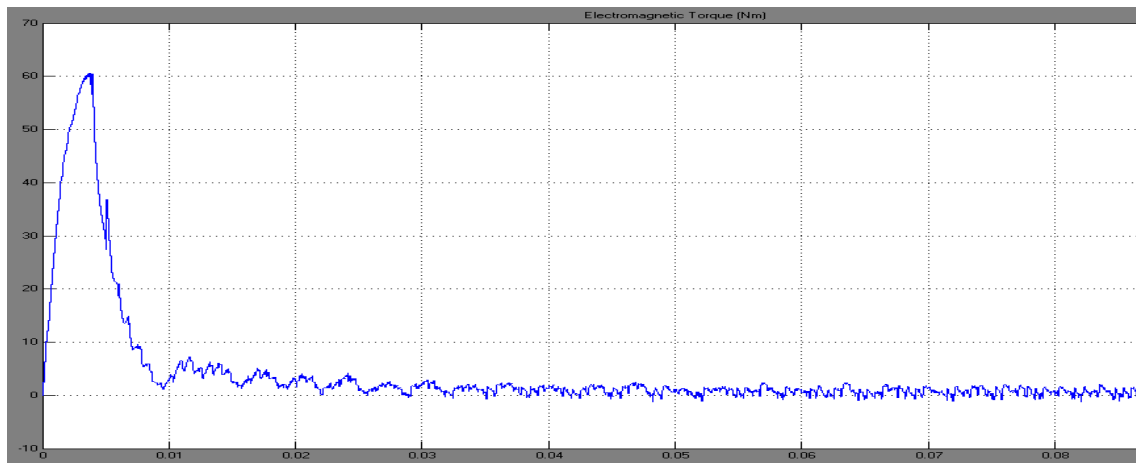


Fig. 9 BLDC Motor Torque

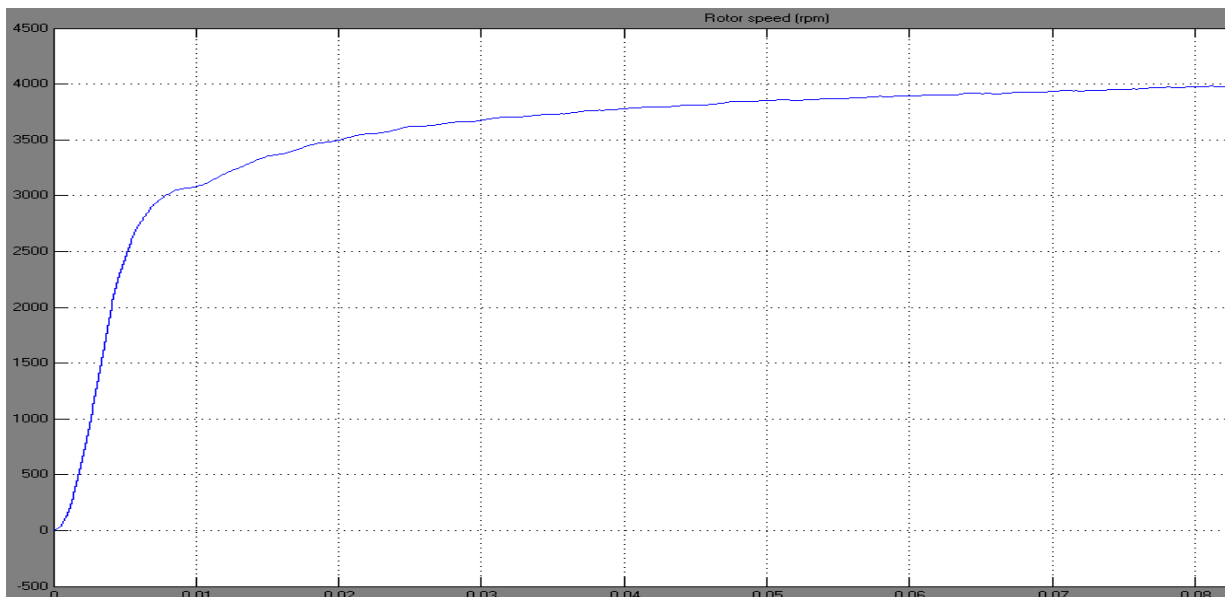


Fig. 10 BLDC Motor speed



## X. CONCLUSION

In this paper, a novel topology is proposed where two active filter inverters are connected with tapped reactors to share the compensation currents. The proposed active filter topology produces nine voltage levels, which significantly reduces the size of passive components. A current balancing algorithm is proposed to keep the reactor magnetizing current to a minimum. The proposed topology is implemented to BLDC Motor Drive to check its performance. It is shown through simulation results, the proposed active filter can achieve high overall system performance.

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