POWER FACTOR CORRECTION OF SINGLE PHASE RECTIFIER BASED ON TWO QUADRANT SHUNT ACTIVE FILTER

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Abstract –This paper presents a new technique to improve the input power factor of a single-phase rectifier with output inductor, based on a two-quadrant shunt active power filter. This is based on a conventional bidirectional DC-DC converter, which is connected to the output side of the diode bridge. Shunt active power filters consist of a power electronic converter which injects a compensating current to the grid, with the harmonic contents equal to the nonlinear load, but with opposite phase, resulting in a sinusoidal grid current, in phase with the voltage achieving an unity input power factor. The active power filter to this rectifier topology enabled the extension of the rectifier operation range in the continuous conduction mode with regulated output voltage. Circuit description, operation principle, modelling, design and simulation results are presented in this paper.

Index Terms — Active power filter, power factor correction, two-quadrant, single-phase inductive filter rectifier.

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I. INTRODUCTION

The increase of electronic devices, such as static power converters, on industrial, commercial and residential circuits, drawing non-sinusoidal currents, pollutes the utility due to the current harmonics generated by them. Several problems arise from the non-linear loads, such as: low power factor, low efficiency, interference by EMI, distortion of the line voltage, among others. The devices which present this characteristic are known as nonlinear loads. Harmonic mitigation methods. The standard regulations and recommendations, like the IEC61000-3-2 (limits the harmonics for equipment up to 16A) and the IEEE 519 (limits the harmonics at the service entrance), enforce to limit the harmonic pollution.

The single-phase diode rectifier is a nonlinear load, which is mainly used in industry for providing DC loads or DC-DC inverters and converters. The conventional single-phase rectifier consists of a full-bridge diode rectifier followed by a capacitive filter, which presents an input current with impulsive characteristic, resulting in a high total harmonic distortion (THD) and a poor input power factor. Many passive and active methods for the input current harmonic distortion reduction applied to this rectifier.The passive filter are a classical solution for the non-linear load problem. However, they have large size, fixed compensation characteristics and resonance problems. The generation of current harmonics are prevented by the high power factor switching mode power supplies.In which the cost of equipment substitution limits its usage to some specific applications, like for instance in the telecommunication field. The shunt active power filter(APF), shown in Fig. 1, is a very interesting solution for the non-linear load problem because it compensates for the load current harmonics and provides the load reactive power, so that the AC mains supplies only the active power. The APF may compensate for any kind of load and may adapt itself for the load changes. And as it is connected in parallel to the AC mains it does not require equipment substitution.

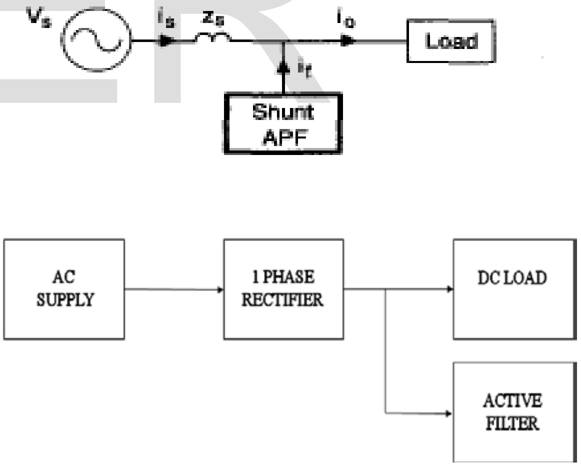


Fig.1.Block Diagram of Shunt APF

Another example of usual nonlinear load is the single-phase rectifier with output inductor, which is commonly used in industry applications where high output current is demanded. The addition of an inductor on the diode bridge output allows the rectifier input current peak reduction and, therefore, its total distortion harmonic reduction and the input power factor improvement. Thus, the reactive power flow from this rectifier is smaller than the conventional one.

However, two drawbacks of this rectifier topology must be emphasized: the inductor large size and the possible resonance between the output capacitor and inductor. For the inductive filter rectifier, a passive method for input current harmonic mitigation was proposed in [1]. The input power factor of this topology was improved. Nevertheless, the rectifier operation was in the discontinuous conduction mode (DCM), not allowing the output voltage regulation. In [2], an active power filter was used for input current harmonic reduction applied to this rectifier topology operating as the nonlinear load. However, as the APF was connected to the alternating current (AC) side of the rectifier, for a load value in which the original rectifier operated in the DCM, the APF insertion to the system was not capable of changing the rectifier operation mode, resulting in no output voltage regulation. The application of a shunt active power filter, for current harmonics reduction, applied to an inductive filter rectifier will process a smaller amount of reactive power than in the case of a conventional rectifier, if the same active power flow is taken into account.

In this paper, a new technique to improve the input power factor of a single-phase rectifier with output inductor, based on a two-quadrant shunt active power filter, is proposed [10]. Still, the application of the proposed APF to this rectifier topology enabled the extension of the rectifier operation range in the continuous conduction mode (CCM), in other words, with regulated output voltage.

II.PROPOSED SYSTEM OF SHUNT ACTIVE FILTER

Shunt active power filter compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by180. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor.

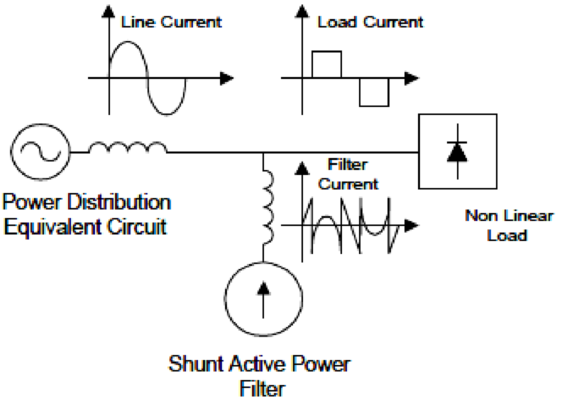


Fig 2. Current Compensation Characteristic of Shunt APF

Non-linear loads, especially power electronic loads, create harmonic currents and voltages in the power systems. For many years, various active power filters (APF) have been developed to suppress the harmonics, as well as compensate for reactive power, so that the utility grid will supply sinusoidal voltage and current with unity power factor. Conventionally, the shunt type APF acts to eliminate the reactive power and harmonic currents produced by non-linear loads from the grid current by injecting compensating currents intended to result in sinusoidal grid current with unity power factor. This filter has been proven to be effective in compensating harmonic current sources, but it cannot properly compensate for harmonic voltage sources. Many electronic appliances, such as switched mode power supplies and electronic ballasts, are harmonic voltage sources.

The active power filter (APF) topology consists in a bidirectional DC-DC converter with capacitive energy storage. This converter presents the same operation stages of a VSI converter used on conventional single-phase APF application for the positive half-cycle of input voltage. The proposed APF converter is connected on the DC side of a rectifier followed by an inductive filter. The active filter operation results in input side power factor correction and input current harmonic contents reduction. In addition, the extension of the operating range on continuous conduction mode for this rectifier is another motivation for this proposed APF application. The active filter operation results in input side power factor correction and input current harmonic contents reduction. In addition, the extension of the operating range on continuous conduction mode for this rectifier is another motivation for this APF application. This shunt active filter works as a buck-boost converter (where the diode is replaced by another MOSFET or IGBT) as regulated output voltage is got at the load. The operation of the shunt active filter as shown in figure is that one switch is ON at positive cycle and another switch is ON during another cycle.

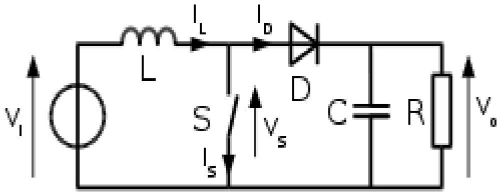


Fig.3. Operation of Shunt Active Filter

A. Pure Active Filters For Power Conditioning

Pure active filters can be classified into shunt (parallel) active filters and series active filters from their circuit configurations. At present, shunt active filters are more preferable than series active filters in terms of form and function, and therefore series active filters are suitable exclusively for harmonic filtering. Figure shows a system configuration of a single-phase or three-phase shunt active filter for harmonic-current filtering of a single-phase or three-phase diode rectifier with a capacitive dc load. This active filter is one of the most fundamental system configurations among various types of pure and hybrid active filters.

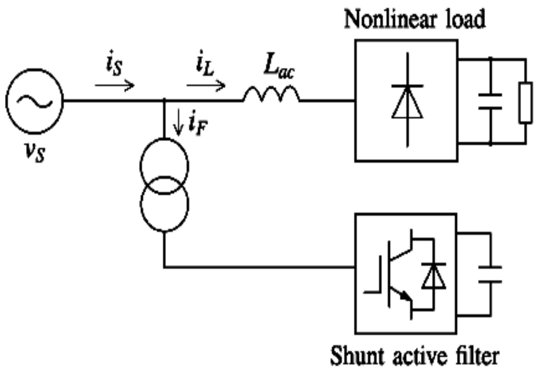


Fig 4. SAF for harmonic-current filtering with a capacitive dc load

B.Circuit Configurations of Shunt and Series Active Filters

This active filter is one of the most fundamental system configurations among various types of pure and hybrid active filters. The dc load may be considered as an ac motor driven by a voltage-source PWM inverter in many cases. This active filter with or without a transformer is connected in parallel with the harmonic-producing load. The active filter can be controlled on the basis of the following "feedforward" manner:

The controller detects the instantaneous load current i_L. It extracts the harmonic current i_{Lh} from the detected load current by means of digital signal processing. The active filter draws the compensating current ($i_{AF} = -i_{Lh}$) from the utility supply voltage V_s, so as to cancel out the harmonic current. so as to cancel out the harmonic current.

III.CONDUCTION MODE

This rectifier can operate in the continuous conduction mode (CCM), when the load inductor current never reaches zero and, consequently, the diode bridge is always conducting. When operating in this mode, the load output voltage, Vo, depends only on the effective input voltage, as shown in expression

$$\mathrm{Vo\ (CCM)} = 0.9V_{o\ (ref)}$$

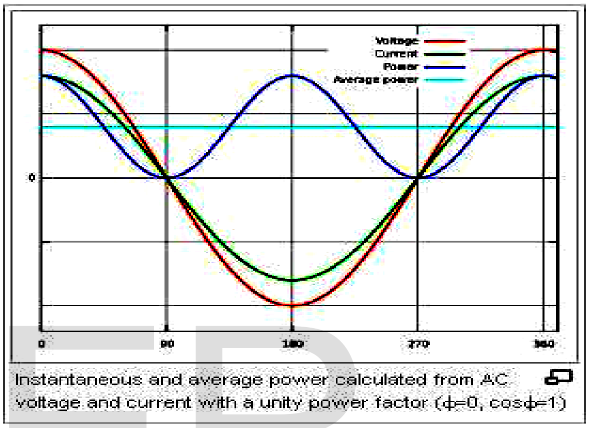
On the other hand, the operation in the discontinuous conduction mode (DCM) occurs when the load inductor current goes to zero for a period of time, resulting on the diodes conduction block. When operating in the DCM, this rectifier presents a varying load output voltage characteristic which depends on two parameters: the effective input voltage and the load current value. For very low current load values, the output voltage can achieve the input voltage peak.

A. Unity Power Factor

Instantaneous and average power calculated from AC voltage and current with a unity power factor (φ=0, cosφ=1).Since the blue line is above the axis, all power is real power consumed by the load.

Instantaneous and average power calculated from AC voltage and current with a zero power factor (φ=90, cosφ=0). The blue line shows all the power is stored temporarily in the load during the first quarter cycle and returned to the grid during the second quarter cycle, so no real power is consumed.

Instantaneous and average power calculated from AC voltage and current with a lagging power factor (φ=45, cosφ=0.71). The blue line shows some of the power is returned to the grid during the part of the cycle labelled φ.



Instantaneous and average power calculated from AC voltage and current with a unity power factor (ϕ=0, cosϕ=1)

Fig 5 Waveform for Unity Power Factor

Thus to reduce the input current harmonic the input current is made sinusoidal (in phase with the input voltage). This is power factor correction (PFC) called as unity power factor.

IV.SYSTEM MODELING AND CONTROL STRATEGY

There are two main control strategies used in single-phase active power filter control: the active power filter current control and input current control. Both strategies require voltage and current control. The APF DC-link voltage (V_{cf}) control is responsible for the system active power flow control, since the APF active power flow must be zero, besides the components losses. The current control is responsible for the input current shape control, which must be a sine waveform in phase with the input voltage

A. Control Strategy

The control strategy applied here is based on the average current mode control, using the rectified input current as the control variable, which is similar to the input current control strategy. This strategy is effective and simple, because it uses only one current sensor, and load current harmonic contents calculation is not necessary.

A few changes on this strategy were needed due to the inductor-capacitor load resonance issue. For solving this problem, a band-stop filter, FN(s), with the rejection center frequency tuned in the load resonance frequency, was used in the APF DC-link voltage monitoring. Therefore, the signal applied on voltage loop control presented its resonance frequency oscillations attenuated, not interfering on the system control. The voltage controller also had to be configured with a low cutoff frequency, resulting in an active power flow control strongly slow. By that, the transient voltage and current oscillations were increased, exceeding design limits and compromising the system operation. For solving the dynamic active power flow control problem, a feed-forward control of the load output current was necessary.

Due to the low components losses in the APF converter, it is considered that the load average active power is the same as the input one. Then, using expression, the average load output current is related to the input current peak .It is seen that the system active power flow can be controlled through the load output current value. The constant gain used in the feed-forward output current loop for the system active power flow control. In addition, the APF DC-link voltage control is used for APF losses compensation.

$$P_o=P_{in}$$

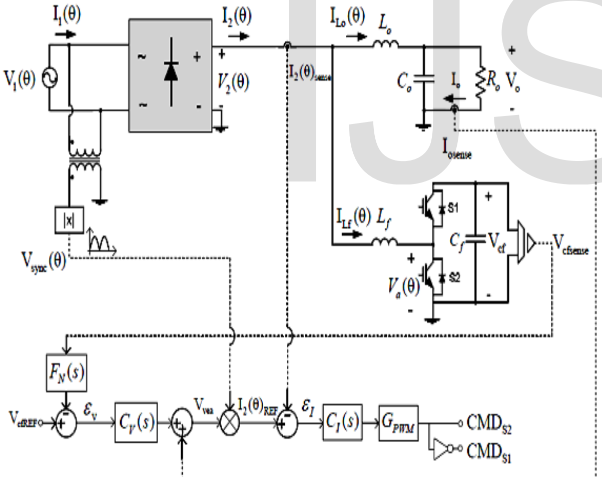


Fig 6 Block Diagram of Control Strategy

$$V_o I_o = \frac{(V_{1p}.I_{1p})}{2}$$

$$I_o = \frac{4}{\pi} I_{1p}$$

Fig 8 Open Loop Simulation For UPF

$$K_{Io} = \frac{4}{\pi}$$

V.SIMULATION RESULTS

A. Open Loop Circuit

The open loop circuit is built in simulink which is a part of the MATLAB software. The switching frequency implemented is 100kHz for the IGBT's. The capacitance implemented in the SAF and the output filter is 4700uF. The inductance implemented for the CCM mode is 30mH and for the SAF is 1.4mH. The resistive load is 13ohms. For 325VAC, 23A input, under unity power factor the output voltage after PFC is 208V and output of the bridge rectifier is 325V. The simulation is represented in open-loop model and the results are presented.

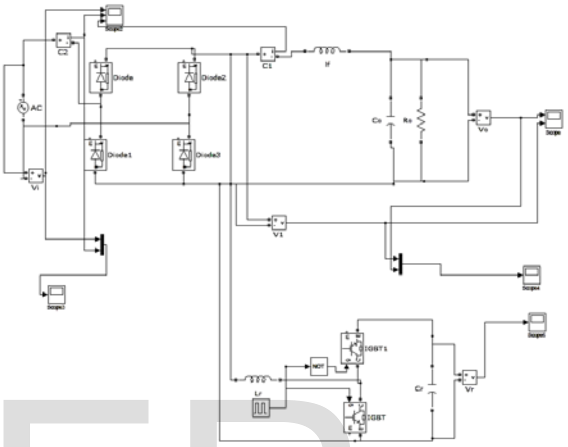
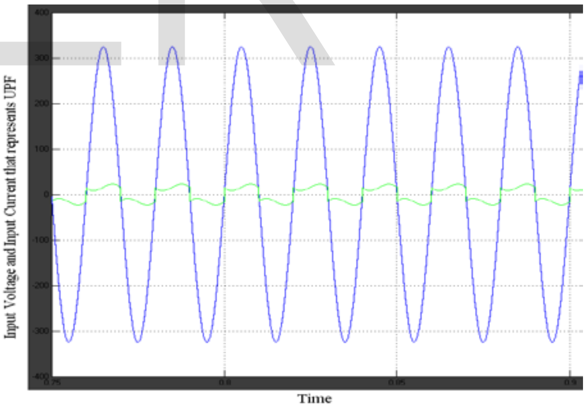


Fig 7 Open Loop Simulation



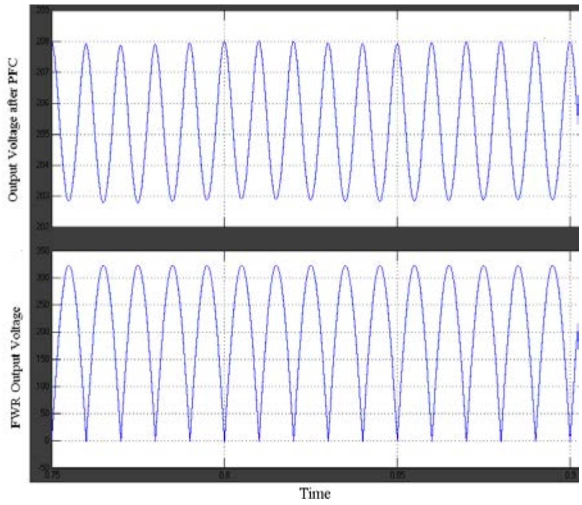


Fig 9 Waveform of Power correction and the FWR output

B. Closed Loop Circuit

The closed loop circuit is implemented in simulink which is a part of the MATLAB software. The switching frequency implemented for the SAF is 100 kHz. The capacitance implemented in the SAF and the output filter is 4700uF. The inductance implemented for the CCM mode is 30mH and for the SAF is 500mH. The resistive load is 13ohms. For 325V, AC, 55A input, under unity power factor the output voltage after PFC is 260V and output of the bridge rectifier is 325V. The simulation is represented in closed-loop model and the results are presented.

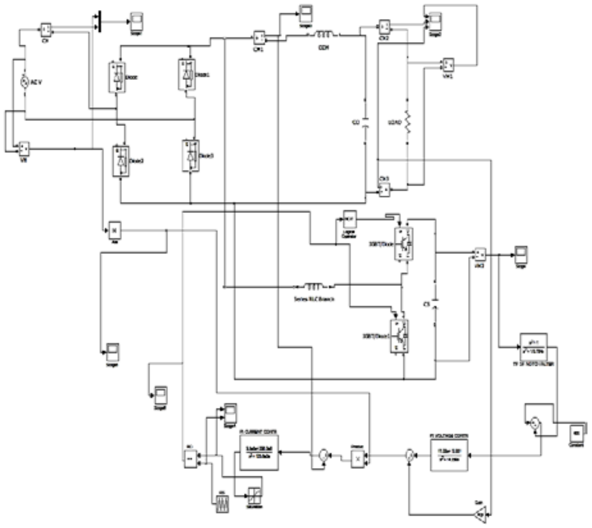
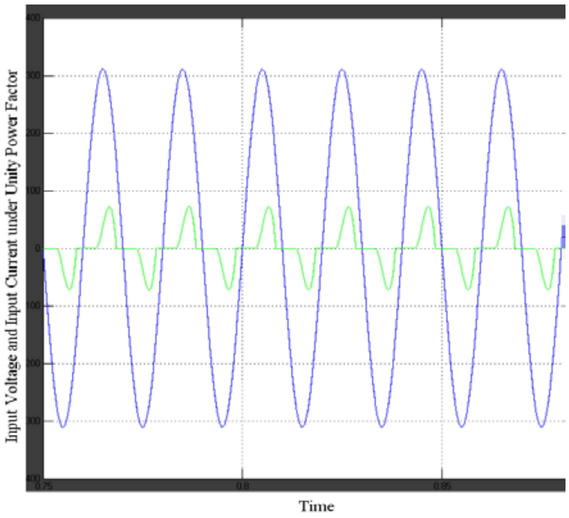


Fig 10 Closed Loop Simulation

A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted by P, I, and D. Heuristically, these values can be interpreted in terms of time P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, or the power supplied to a heating element.

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, K_d. The derivative term slows the rate of change of the controller output. Derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, the derivative term slows the transient response of the controller. Also, differentiation of a signal amplifies noise and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large. So in this paper PI controller is implemented according to the controller type that has been explained by Bode plots.



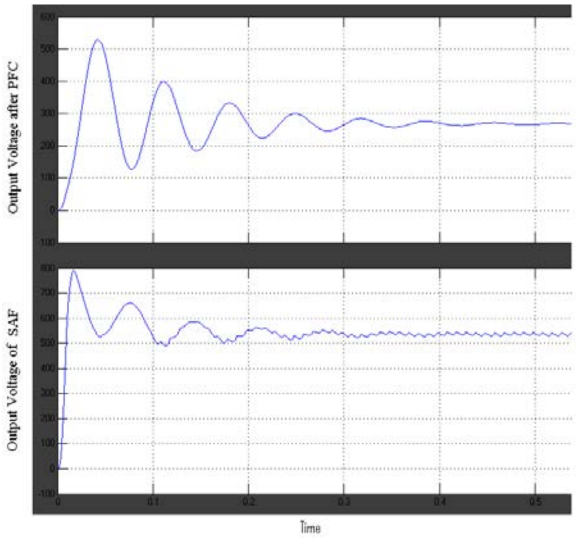


Fig 11 Closed Loop Circuit Waveform

VI. CONCLUSION:

Shunt active power filters (APF) consist of a power electronic converter which injects a compensating current to the grid, with the harmonic contents equal to the nonlinear load, but with opposite phase, resulting in a sinusoidal grid current, in phase with the voltage achieving an unity input power factor. In this paper a new technique to improve the input power factor of a single-phase rectifier with output inductor, based on a two-quadrant shunt active power filter, is proposed. Still, the application of the proposed APF to this rectifier topology enabled the extension of the rectifier operation range in the continuous conduction mode (CCM), in other words, with regulated output voltage.

Thus this presents a new technique to improve the input power factor of a single-phase rectifier followed by an inductive filter. It consists in the employment of a two-quadrant active power filter, based on a conventional bidirectional DC-DC converter, connected to the output side of the diode bridge. This technique allows the extension of this rectifier range operation in the continuous conduction mode.

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