Design and Simulation of Control strategies for Voltage Source PWM Rectifier

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Abstract— Power Electronics is defined as branch of science, engineering and technology which deals with Power Electronics Modulators (PEM) in which efficient conversion, conditioning, processing, controlling and modulating the flow of large electric power using Solid State Power Semiconductor Device (SSPSD) in order to supply high quality power to the load which causes minimum pollution of physical characteristics of electric power with regulating stability and response characteristics of the closed loop system and its application. Diode rectified circuit and thyristor rectifiers circuit are widely used in the conventional rectifier circuit, but the problems arising during operating should not be ignored, such as, harmonic problems and low power factor. These problems may do harm to the grid, which in turn cause a series consequences, therefore, the application of such rectifier will be limited. With the continuous development of PWM technology people pay attention to the PWM rectifier gradually. The paper first analyzes the mathematical model of three-phase voltage-source PWM rectifier and then introduces double closed-loop control of voltage and current system, in which the active and reactive power can be controlled independently. PWM rectifier control system is built based on the DSP2812 after modeling and simulating in MATLAB / SIMULINK environment. The result shows that the system has the characteristic of good anti-interference performance and fast dynamic response.

Keywords- *AC-DC Converter, Current Wave Shaping, Power Factor Correction, Harmonics, Switch Mode Rectifier, Power Quality*

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I. Introduction

Power Electronics Design is a creative decision making process for identifying needs of Power Electronics Modulators (PEM) in which the basic science, mathematics and engineering science are applied to devising a solution that may be product, a technique, a structure, a project, a method or many other things depending on the problem to fill those needs and use of resource optimally to meet a stated objectives.

Most of the more important international standards define Power Quality (PQ) as a set of electrical boundaries of electric supply provide under normal operating condition that allows equipment to function in its intended manner without significant loss of its performance in ratings, class, efficiency and life expectancy that do not disrupt or disturb consumer’s process. Performance degradation results when the electrical power applied to equipment is deficient. [1]

A Power Electronics equipment providing dynamic and adjustable solution to PQ problem to decrease the severity of harmonic pollution in the network is called Active Power Filter (APF) or Power Line Conditioners (PLC). [2]

The PLCs are able to compensate voltage & current harmonic, reactive power, regulate terminal voltage, supply flickers and improve voltage balance in 3- Φ system.[3] Because of the following reason any PEC requires HFSMR in AC- DC Conversion:

1. The proliferation of microelectronics processes in a wide range of equipment have increased the vulnerability of such equipment to PQ problem.
2. PQ problems includes a variety of electrical disturbance which may originate in a several ways and have different effects on various kinds of sensitive loads.
3. PQ problems were considered minor variation in power quality usually unnoticed in the operation of conventional equipment, may bring whole setup to standstill.
4. The proliferation of Non Linear Load (NLL) with large rated power has increased the contamination level in voltage and current waveforms, forcing to improve compensation characteristics required to satisfy more and more stringent harmonic standards.[4]

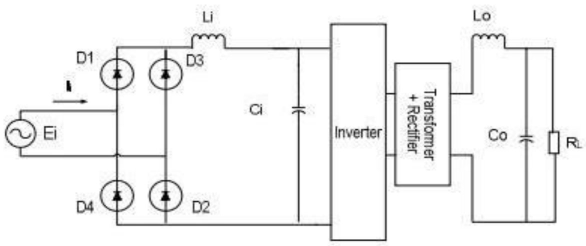

Fig.1 VSF SMR Converter

As a result of this vulnerability, increasing number of industrial and commercial facilities are trying to protect themselves by investing more sophisticate equipment to improve PQ. The main design objective in any High-Frequency SMR converter is to minimize the size and weight while maintaining acceptable component stresses. An increase in the switching frequency is the most basic technique used for size reduction because the volume of the converter depends mainly on the size of the magnetic components and associated filter capacitors. Further reduction in the size of the converter can be obtained by operating the converter with continuous input and output currents and by optimizing the usage of power semiconductor switches,[5], [6].

Active Front End (AFE) converters use semiconductor switches (such as IGBTs) as rectifiers instead of the diode bridges which are otherwise generally used. For the control of electric power or power conditioning, the conversion of electric power from one form to another is necessary. The static power converters perform these functions of power conversions. A diode bridge rectifier circuit converts AC voltage into a fixed DC voltage and is the most commonly used topology because of its simple construction, low cost and high reliability. The diode bridge rectifier forms a part of the power circuit in many applications. At lower power levels, the application is in the area of computers, telecommunications, air-conditioning, battery charging etc. At higher power levels, the application is in industries like for AC and DC drives. In case of AC drives, a diode bridge rectifier provides the necessary DC bus voltage which acts as an input to the inverter. In all these applications, a large capacitor is normally used at the output stage of the bridge rectifier to reduce the DC output ripple. This diode bridge rectifier with a large output capacitor will have a highly distorted, non-sinusoidal input current with a lot of lower order harmonics and very poor power factor. In this work, the input current to the diode bridge rectifier is made sinusoidal and in phase with the input voltage to get unity power factor. We are used active front end converter.

Active front end (also known as active rectifiers) actively converts between AC and DC power. A simple Active Rectifier definition is “a non-isolated AC-DC converter with two key benefits over passive rectifier systems; output voltage regulation, and AC input harmonic reduction.” The term “Active Front-end” describes the same thing, while eliminating the term “rectifier”, which I think incorrectly, implies a unidirectional converter. Rather than “output voltage”, I like to use the term “DC link voltage”, since as we’ve noted, the converter is inherently bi-directional, and thus the DC side can be the output or input. You can see where this is going. Call it what you like, an active front-end or active rectifier has the ability to transfer power from the DC link to the AC line. 1.2 Active Front-End Characteristics • Active and reactive power flow can be controlled in both directions and independently. • Possibility for sinusoidal current drawn from, or delivered to, the power grid • Small filter requirements compared to traditional Thyristor converters • The DC-link voltage level can be controlled • Can be used as the only power source in an AC network(stand-alone application) • Can inject currents to compensate for non-linear loads or for transients (e.g. operating as an active filter) • Very short response time (step changes in active / reactive power and current in less than a ms).[7] 1.3 AFE Features • Regenerative feedback into the line supply (four-quadrant operation) • Sinusoidal line currents – low harmonics are fed back into the line supply • No commutation faults when the power fails in regenerative operation • Line supply voltage fluctuations are compensated • Extremely high drive dynamic performance • Selectable power factor[7]

II. Classification of SMR

The SMRs possess many categories in circuit topology and switching control approaches. A single-phase boost-type SMR is shown in Fig. 2(a), and the typical waveforms of ac current using low-frequency (LF) and high-frequency (HF) switching are sketched in Figs. 2(b) and 2(c). The features of HF-SMR comparing to LF-SMR are: (i) more complicated in control; (ii) high control performances in line drawn current, power factor and output voltage; (iii) lower efficiency. [7]

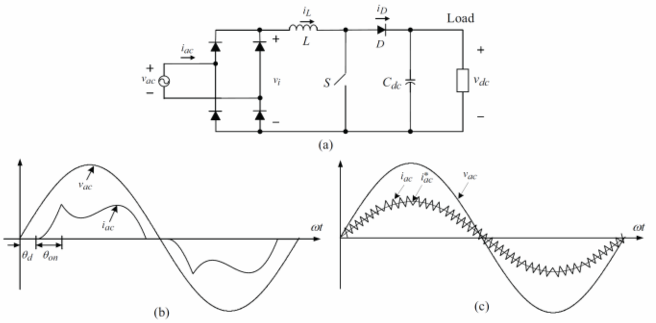

Fig. 2. Boost-type SMR: (a) circuit; (b) sketched key waveforms for low-frequency switching; (c) sketched waveforms for high-frequency switching

Basically, a SMR is formed by inserting a suited AC/DC converter between diode rectifier and capacitive output filter, under well-regulated DC output voltage, the desired AC input line drawn power quality can be achieved. The existing SMRs can be categorized as:

1. Classification based on Schematics

a. *Single-phase or three-phase*: each category still possesses a lot of types of SMR schematics. The three-phase SMR will be a natural choice for larger power plants.

b. *Non-isolated or isolated:* although the former SMR is simpler and more compact, the latter one should be used if the galvanic isolation from mains is required. See for example, the fly back SMR is gradually employed in communication distributed power architecture as a single-stage SMR front-end, or called silver box, to establish -48V DC bus voltage.

c. *Voltage buck, boost or buck/boost:* depending on the input-output relative voltage levels, suited type of SMR and its control scheme should be chosen. Basically, the boost type SMR possesses the best current control ability subject to having high DC output voltage level.

d. *Single-stage or multi-stage:* generally speaking, the stage number should be kept as small as possible for achieving higher efficiency and system compactness. Hence, single-stage SMR is preferable if possible.

e. *One-quadrant or multi-quadrant: multiple quadrant* SMR may possess reverse power flow from DC side to AC source, such as the regenerative braking of a SMR-fed AC motor drive can be performed by sending braking energy back to the utility grid.

f. *Hard-switching or soft-switching:* Similarly, suited soft switching technique can also be applied to reduce the switching loss, switching stress and EMI of a SMR.

2. Classification based on Control Methods:

a. *Low-frequency control:* only v-loop is needed and only one switching per half AC cycle is applied. It is simple but has limited power quality characteristics.

b. *High-frequency control-* voltage-follower control: without current control loop, only some specific SMRs operating in DCM possess this feature, see for example, buck-boost SMR and fly back SMR.

c. *High-frequency control- standard control:* it belongs to multiplier-based current-mode control approach with both v- and i- control loops.

A growing number of current wave shaping method applied to single phase rectifier are now available including active, passive and hybrid methods [8]. Among the proposed AWS methods, the CSF method as in [9] is superior to the others in reducing the input PF. Also Passive Wave Shaping Method as in [10], [11] proposed by the author to reduced THD_i and increase PF. This paper presents a comparative evaluation of two previous method.

III. HIGH FREQUENCY VOLTAGE SOURCE FED SWITCHED MODE RECTIFIER

PEM typically use a Front End Single Phase Diode Rectifier (FESPDR) feeding the respective DC bus capacitors through a very low inductance path. This approach has many disadvantage including:

1. Higher input Current harmonic components.
2. Lower rectifier efficiency because of the large rms value of the input current.
3. Input ac mains voltage distortion because of the associated higher peak currents.

In this section the VSFSMR converter is designed and analyzed under steady-state condition. The converter is analyzed under the following assumptions:

1. All switching devices are ideal and the forward drop and reverse leakage currents of the diode are negligible.
2. The filter components are lossless;
3. The high frequency transformer turns ration is 1:1.
4. The filter capacitor C is assumed to be sufficiently large so that the DC bus voltage is practically ripple free.
5. The ac source is considered is ideal.
6. The load is modeled as a variable resistance since the effect of high frequency ripple current I is negligible as per assumption 4.

Regarding the Fig.1 the high frequency inverter duty cycle is varied to counter act input voltage and load fluctuations. For minimum input voltage and rated load the inverter switch duty cycle will be maximum. For maximum input voltage and light load the inverter switch duty cycle D will be minimum. The converter is to be analyzed under worst operating conditions and for DC bus voltage of ± 20 %.

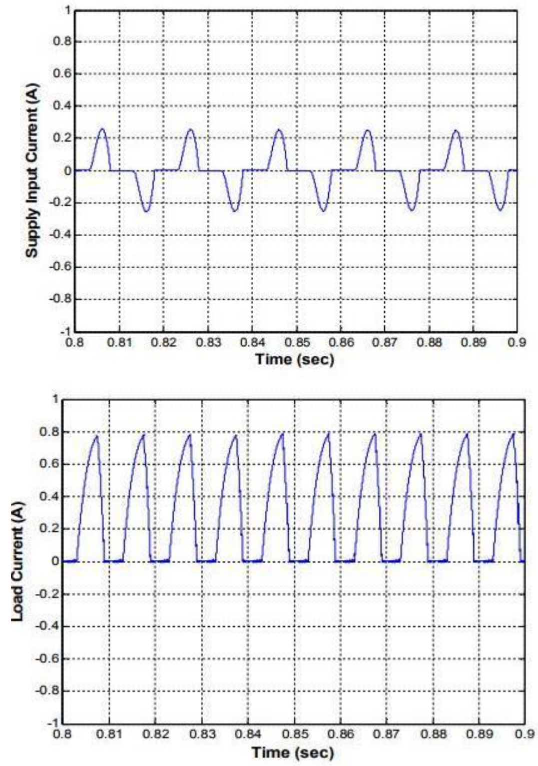

Fig. 3 VSF Supply Input Current and Load Current

In order to illustrate the significance and facilitate the understanding of the characteristic s of VSF circuit, the following design example is presented:

The SMR Converter has the following specifications:

TABLE I
SPECIFICATION OF SMR CONVERTER

Output power	15 W = 1.0 p.u.
Minimum rms input voltage	8.5 V = 1.0 p.u.
Inverter Operating frequency	10 KHz
Output Current ripple	10 % peak to peak

From this values parameter of the converter are:

TABLE II
COMPONENT SPECIFICATION OF VSF SMR CONVERTER

1 pu current	1.7647 A
1 pu impedance	4.8167 Ω
1 pu inductance	153. mH
1 pu capacitance	660.85 μF
Eirms	8.5 V
F	50 Hz
Li	10 mH(parasitic)
Ci	19134 μF
Lo	0.4 mH
Co	17314 μF
ZL	2.8 Ω

The supply and load current shown in Fig. 4 and Fig. 5 respectively appeared as pulsed signal so it is high distorted waveform. Also, THDi = 116 % and PF= 0.633.

IV. HIGH FREQUENCY CURRENT SOURCE FED SWITCHED MODE RECTIFIER

In case of CSF SMR converter the duty cycle and the frequency of the boost switch is varied for input voltage variations.

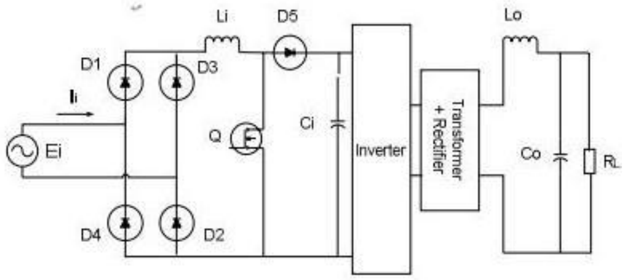

Fig. 4 CSF SMR Converter

The converter is design and analyzed under the following assumptions where application, same as the assumption used for the design of the VSF SMR Converter:

1. All the switching devices are ideal and the forward voltage drop and reverse leakage currents of the diode are negligible.
2. The filter components are lossless.
3. The load voltage and the inverter input voltage are assumed to be ripple free.
4. The high frequency transformer turns ratio is 1:1.
5. The ac source is ideal.

The SMR converter has the same specification as shown in Table 1 the component specification for CSF are as follows:

TABLE III
COMPONENT SPECIFICATION OF CSF SMR CONVERTER

1 pu current	1.7647 A
1 pu impedance	4.8167 Ω
1 pu inductance	153. mH
1 pu capacitance	660.85 μF
Eirms	8.5 V
F	50 Hz
Li	0.4950 mH (parasitic)
Ci	38924 μF
Lo	0.104 mH
Co	8260.6 μF
ZL	2.8 Ω

It is clear seen from Table 4 that by varying D the THD, PF and 3rd harmonics varies. From the Table it is found that at D =0.8 the THD reduced to 69 % and if it is compared with VSF SMR in section II. Authors conclude that CSF SMR reduce the harmonic distortion. Also the PF increase to 0.81 which is higher in the case of VSF SMR.

Compared with passive filter, Active Power Filter (APF) has the higher control ability to compensate load reactive and harmonic current components. Taking the shunt type active power filter as an example, a controlled current is generated from the APF to compensate the load ripple current as far as possible.

TABLE IV
THD, PF and 3rd ORDER HARMONIC FOR DIFFERENT VALUEOF DUTY CYCLE

Duty Cycle	THD_i (%)	PF	3rd (%)
0.4	119	0.62	42.85
0.5	128	0.58	50.1
0.6	114	0.61	42.7
0.7	78	0.77	35.2
0.8	69	0.81	31.1
0.9	81	0.76	39.4

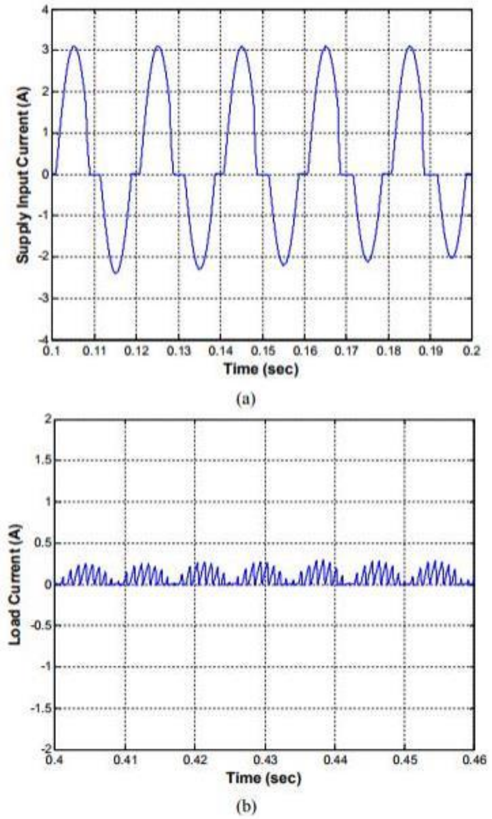

Fig. 5 CSF Supply Input Current and Load Current

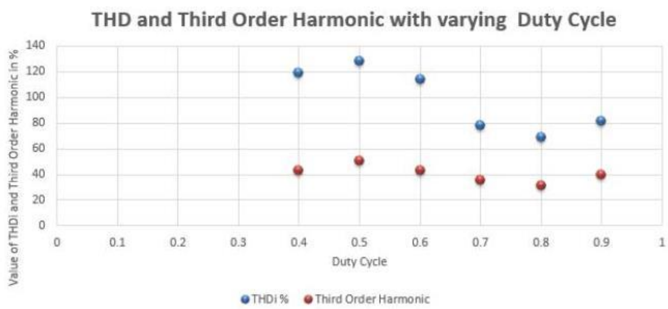

Fig. 6 Variation of THD_i and 3rd order harmonic with respect to duty cycle.

V. PASSIVE WAVE SHAPING METHOD

In this section wave shaping method proposed as in [5] used to design passive wave shaping filter to reduce THDi and improve PF. Assumption 1, 2 and 5 in Section II are valid here. The same input that used for VSF are going to be use here to design passive filter as follows:

TABLE V
COMPONENT SPECIFICATION OF PASSIVE WAVESHAPING FILTER

1 pu current	1.7647 A
1 pu impedance	4.8167 Ω
1 pu inductance	153. mH
1 pu capacitance	660.85 μF
Eirms	8.5 V
F	50 Hz
Li	4.7 mH
Ci	238 μF
Lo	0.5 mH
Co	3.1 μF
ZL	2.8 Ω

The PF improved to be 0.86 in this case compare with VSF (0.63) and CSF (0.81). Table VI illustrate a comparison between the harmonic distortions of the three methods. It is clear that THD_i in the passive method is 56.2 % which is less in comparison with that of VSF (116%) and CSF (69%).

Also the 3^{rd} harmonic was reduced in the passive method but it seen that the 9^{th} and 11^{th} harmonic are increased. The supply current waveforms in Fig. 5 and Fig. 6 are more close to the sinusoidal waveform in comparison with that of Fig.4 which lead to less harmonic distortion.

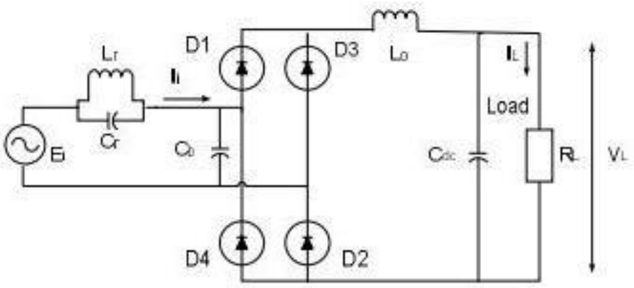

Fig. 7 Passive Wave Shaping Filter

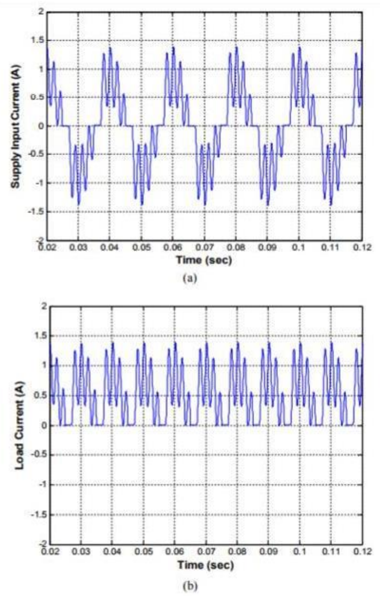

Fig. 8 Passive Wave Shaping method Supply input current and Load Current.

The advantage of Passive Wave Shaping Filter as follows:

1. Well-designed passive filter can be implemented in larger sizes of MVAR of ratings and prove almost maintenance free service.
2. These are more economical to implement than their counter parts like synchronous condenser.
3. A fast response time of the order of one cycle of less can be obtained, which is important for correction of flickering voltage dips due to arc furnace loads.
4. Unlike rotating power capacitors do no contribute to the short circuit current.
5. A single installation can serve many purposes like reactive power compensation, reducing THD to acceptable limits, voltage support on critical buses in case of source outage and reducing the starting impact and voltage drop of large motors.
6. When a choice is available between Active & Passive Wave Shaping Filter, it is more economical, less complex, ease control requirement and not required any PEM.

Although Passive Wave Shaping Method suffered from some of the limitations:

1. Fixed Compensation: It will provide fixed compensation. Tuning is very difficult in case of passive filter.
2. Larger Size: The passive filter is bulkier, heavier, costlier and very noisy.
3. Resonance: Source impedance is not accurately known and varies with the system configuration strongly influences filter characterizes of passive filter. [12]

The Shunt Filter acts as a sink to harmonic current flowing through the source in the worst case, the passive filter falls in series resonance with source impedance. At a specific frequency anti resonance or parallel resonance occurs between the source impedance and the shunt passive filter is called harmonic amplifications.

Various series L-C resonant trap filters are connected across the line terminal to attenuate the specific order harmonics. This approach is simple, rugged, reliable and helpful in reducing EMI. However, it is bulky and cannot completely regulate nonlinear loads, and it is needed the redesign adapted to load changes.

VI. CONCLUSION

A comparison between passive and active input current wave shaping methods for single-phase rectifiers has been proposed and the relevant waveforms of the input and output currents obtained from computer simulation have been shown in this paper.

Also, a comparison between improved PF and reduction in THD was shown that the passive method is better than active one in improving PF and reducing THDi .

It is found that use of Active Harmonic Filter increases the input power factor approximately from 0.63 to 0.81. While, in passive filter the PF increased to 0.86. Moreover, Total Harmonic Distortion THDi was reduced in passive method more in comparison with active one when a choice is available between Active & Passive Wave Shaping Filter, it is more economical, less complex, ease control requirement and not required any PEM.

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