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A Quantitative Approach to Minimize Harmonics Elimination Using Filter Design

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Abstract : The aim of this paper is to establish an analytical method for the design of the Improved low pass Broadband Passive harmonic Filter (IBF) that absorbs current harmonics caused by three phase bridge rectifiers used in motor drives. The design attempts to comply with the IEEE Standard 519-1992 recommended harmonic limits applied to the current harmonic limits of three phase rectifier systems. In this paper an analytical design method of the improved broadband passive harmonic filter (IBF) for three phase diode rectifier front-end type adjustable speed drives is presented. The method is based on frequency domain modeling of the rectifier and filter. The success of the method involves accurate representation of the load harmonics. With the harmonics well defined, the harmonic and fundamental frequency equivalent circuits are utilized to analytically calculate the voltages/currents. Thus, the size and the performance of the filter can be optimized. The analytical method is verified via computer simulations and laboratory experiments. Also a performance comparison of various passive harmonic filters for three-phase diode rectifier front-end type adjustable speed drives is provided. The comparison involves the input current total harmonic distortion, input power factor, rectifier voltage regulation, energy efficiency, size, and cost. The parallel/series harmonic resonance problem related issues are addressed and unbalanced operation performance investigated. The comparison is based on analysis and computer simulations and the results are validated by laboratory experiments.

Keywords: ASD, broadband, design, drive, filter, harmonic, power factor, rectifier, THD.

1.0 Introduction

The application of cost effective power converter circuits which enhance the overall performance, efficiency, and reliability of industrial processes is common in all industry. The industrial applications of AC/DC and DC/AC power conversion have increased gradually since the advent of silicon controlled rectifiers (SCR) in 1957. However, the wide use of single and three phase diode/thyristor rectifiers, for DC power supplies, Adjustable Speed Drives (ASD), Uninterruptible Power Supplies (UPS), and for household and industrial appliances, took place in the last two decades. With an estimated 65% of industrial electrical energy used by electric motors, the major users in industry increasingly see energy reduction as a key to improve their profitability and competitiveness. Because variable speed drives reduce energy consumption (20-30% savings) and decrease pollutant emission levels to environment while increasing productivity, their proliferation is inevitable**.** For variable speed applications, ASDs are widely employed in driving induction and permanent magnet motors due to the high static and dynamic performance obtained in such systems. High energy efficiency and high motion quality, low starting torque, etc. are the positive attributes of the ASDs. ASDs, consists of AC/DC converter connected to DC/AC inverter. Of all the modern power electronics converters, the Voltage Source Inverter (VSI) is perhaps the most widely utilized DC/AC conversion device with commonly used Pulse Width Modulation (PWM) methods. The PWM-VSI consists of six power semiconductor switches with anti-parallel feedback diodes. It converts a fixed DC voltage to three phase AC voltages with controllable frequency and magnitude. In AC motor drive applications, typically a rectifier device converts the AC three phase line voltages to DC voltage. Following the rectifier voltage passive filtering stage, the VSI interfaces the DC source with the AC motor to control the shaft speed/position/torque. The most used frontend topology for ASDs is still the 6-pulse diode/thyristor rectifier, due to well-known advantages such as, high efficiency, low cost, robustness and reliability. The main structure of PWM-VSI drive with a 6-pulse diode rectifier front end is shown in Fig. 1.1.

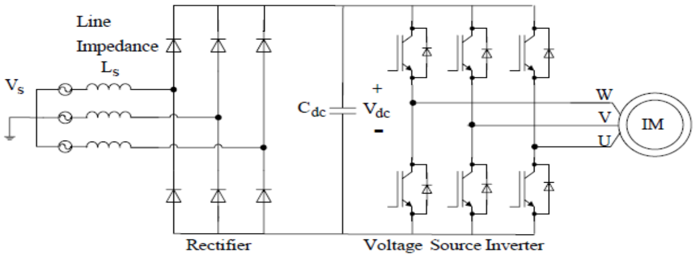

Fig.1.1 The main structure of PWM-VSI diode bridge rectifier front-end AC drive.

Line commutated diode and thyristor rectifiers exhibit nonlinear load characteristics and draw non-sinusoidal currents from the supply even when fed from sinusoidal supply voltages. These harmonic currents are injected into the supply systems and pollute the power line causing power quality problems to many power quality critical loads.

2.0 Harmonic Mitigation Techniques

Various harmonic reduction techniques have been developed to meet the requirements imposed by the current harmonic standards. In general these techniques can be classified into five broad categories:

1. Passive filters (line reactors and/or DC link chokes, series, shunt, and low pass broadband filters)
2. Phase multiplication systems (12-pulse, 18-pulse rectifier systems)
3. Active harmonic compensation systems (series, parallel)
4. Hybrid systems
5. PWM rectifiers (step-up, step-down, VSI, CSI etc.)

The intent of these techniques is to make the input current a pure sinusoidal waveform, so as to reduce the overall current THD. In passive filters, the flow of the undesired harmonic currents into the power system can be prevented by the usage of a high series impedance to block them or by diverting them to a low impedance shunt path. These two methods represent the concept of the series and the shunt passive filters, respectively.

Series passive filters can be purely inductive type or LC tuned type. AC line reactor filter and DC link inductor filter are the two purely inductive type filters. AC line reactors offer a considerable magnitude of inductance that alters the way the current is drawn by the rectifier bridge. They make the current waveform less discontinuous, resulting in lower current harmonics. To maximize the input reactance while minimizing AC voltage drop both AC line reactors and DC link inductance (choke), shown in Fig. 1.2, can be combined. The DC link inductance is electrically present after the diode rectifier and before the DC bus capacitor and it performs very similar to the three phase AC line reactors. Both AC line or DC link inductance insertion methods provide a limited amount of THD reduction that is not sufficient to comply with the IEEE 519 standards.

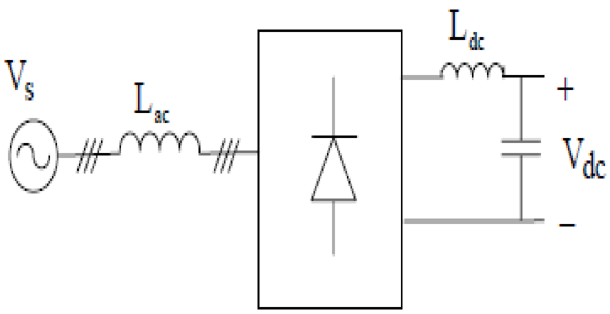

Fig.1.2 AC line reactor and DC line inductance based passive filtering.

3.0 PASSIVE HARMONIC FILTERING METHODS

Although the active filtering technology is well matured and its performance attributes are attractive, the passive filtering technique is still the most common approach for current harmonic mitigation of three phase multi-pulse diode/thyristor rectifier systems. Since all the filter components are passive and rugged, and the filter design and implementation procedure is relatively easy and most importantly the filter cost is low, the passive filtering approach is favorable in most applications. With their simple structure, passive filters have been extensively used for ASD harmonic mitigation to meet the requirements of the IEEE Standard 519 with respect to current TDD limits at the PCC and to voltage distortion THDV at utility supply side. On the contrary to phase multiplication, active filters, hybrid filter systems, and PWM rectifiers, in passive harmonic filtering techniques, no electronic circuits and hardware, and no complicated control algorithms are designed and implemented. Consequently, passive filters are relatively inexpensive means for eliminating current harmonic distortion and improving the system performance. Therefore, passive filters usually have the priority among other effective filtering types. Of the passive harmonic filtering methods, the AC in line reactors, the DC link inductance, shunt tuned filter, and low pass broadband LC filter topologies are discussed in this chapter. General design rules, performance attributes, and the most significant advantages and disadvantages are presented.

3.1 Input Current Harmonic Distortion of ASD Systems

An ASD system with a basic 6-pulse diode bridge rectifier, shown in Fig. 2.1, has typically an input line current waveform and harmonic spectrum as shown in Fig. 2.1. Harmonics generated have 2p±1 order, where p is the number of pulses in the rectifier output DC voltage. In the harmonic spectrum the first four harmonics are dominant (5th, 7th, 11th and 13th). In the illustrated particular case (low system impedance < 2%) the total harmonic current distortion (THDI) is very high > 70% and the current waveform is highly distorted. The harmonic current content of the basic 6-pulse diode bridge rectifier is highly dependent on the grid where the rectifier is connected. In general a high harmonic current distortion (up to 135%) can be expected when the rectifier is connected to a strong grid and a low harmonic current distortion when connected to a weak grid (down to 30%)**.**

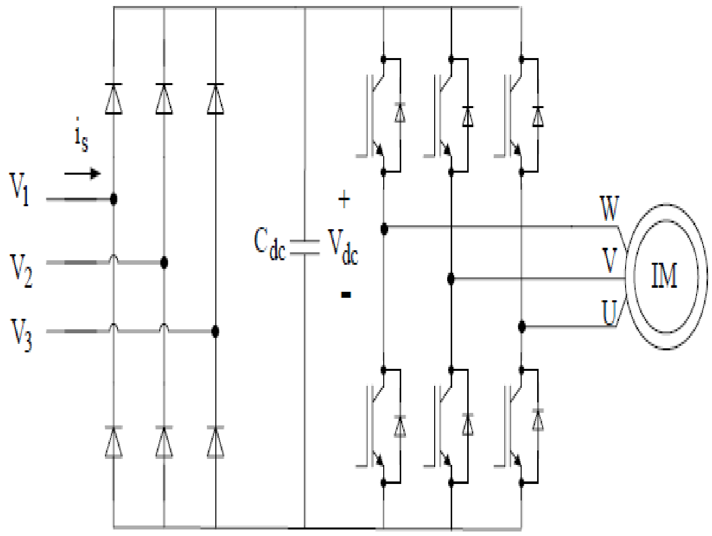

Fig.2.1 Diode bridge rectifier front-end ASD system with no harmonic filters.

4.0 LOWPASS BROADBAND FILTER

In the previous chapter, the common passive filtering methods used for ASD harmonic mitigation were studied. Their general design rules and performance attributes were discussed. Among the passive harmonic filters discussed, the LC low pass broadband filter has been found as a more practical approach for harmonic filtering. The filter has superior performance to the other filtering methods discussed. It is effective in suppressing the rectifier current harmonics, it is simple and free of harmonic resonance problems. However, the simple structure of the filter comes with a serious drawback which is the rectifier terminal over voltages. As a result, the Improved Broadband Filter (IBF) has been developed in order to overcome the deficiency of the LC filter and obtain superior overall performance characteristics. In this paper the IBF topology is under investigation. The filter construction, operating principle, behavior analysis and finally detailed design method are described.

4.1 Low pass Broadband Filter Topology and Its Operating Principle

The IBF circuit topology is configured as shown in Fig. 3.1. The three phase AC power line is connected to a three phase AC input reactor (Li) and to a damping resistor (Rd). The center leg consists of an AC series filter reactor (Lf) and capacitor bank (Cf) which forms a shunt filter. The capacitor bank is usually Δ connected (Cf = CfY = 3CfΔ). Finally, a three phase AC output reactor (Lo) is inserted between the rectifier terminals and the Li-Lf connection terminals of the filter. With an appropriate design, at the dominant rectifier current harmonic frequencies (over a wide frequency range), the large input reactor (Li) provides high impedance (rectifier to line impedance ZRL) with respect to the shunt filter impedance, as shown in Fig. 3.2, so that all rectifier current harmonics will be impeded by the line and diverted to pass through the shunt filter. The line impedance Z line is found and the shunt filter impedance is given by

$$Z_{shunt} = \left| R_{Lf} + j(n\omega_e L_f - \frac{1}{n\omega_e C_f}) \right|$$

where RLf is the filter inductor equivalent series resistor, Lf and Cf are the shunt filter reactor and capacitor, respectively. Not only Li provides sufficient impedance that minimizes current harmonics flow from the rectifier to the AC line, but it also minimizes the effect of the line voltage harmonics on the rectifier as a result of the line to rectifier high impedance ZLR provided at the line dominant harmonics (i.e. provides harmonic isolation between the source and the rectifier). Due to large Li the line voltage harmonics cannot force significant harmonic current on the shunt filter either. Therefore, the duty of Li reactor is to block current harmonic flow either way. As the parallel resonance frequency is lower than the dominant rectifier current harmonic frequencies, the risk of harmonic resonance is avoided. The filter capacitor Cf improves the input power factor by providing full fundamental frequency reactive power compensation. The real power P is flowing from the supply to the load. Lf is partitioned with Li such that there is no overvoltage at the rectifier terminals (unlike the LC filter) and no-load to full-load filter output voltage change is confined within the specified range. The filter components Lf and Cf are connected in series to provide very low series impedance to the rectifier current harmonics and short circuit them through its path. The output reactor (Lo) is a current smoothing reactor that makes the rectifier current waveform less discontinuous, resulting in lower current harmonics. Utilizing Lo reduces the rectifier THDI significantly (by approximately 50%). The reduction in the rectifier current harmonics implies less harmonic current and voltage stress on the shunt branch components Lf and Cf. Hence, smaller, lower cost, and more efficient filter structure. The resistance Rd is employed to damp the voltage/current peaks during switching transients.

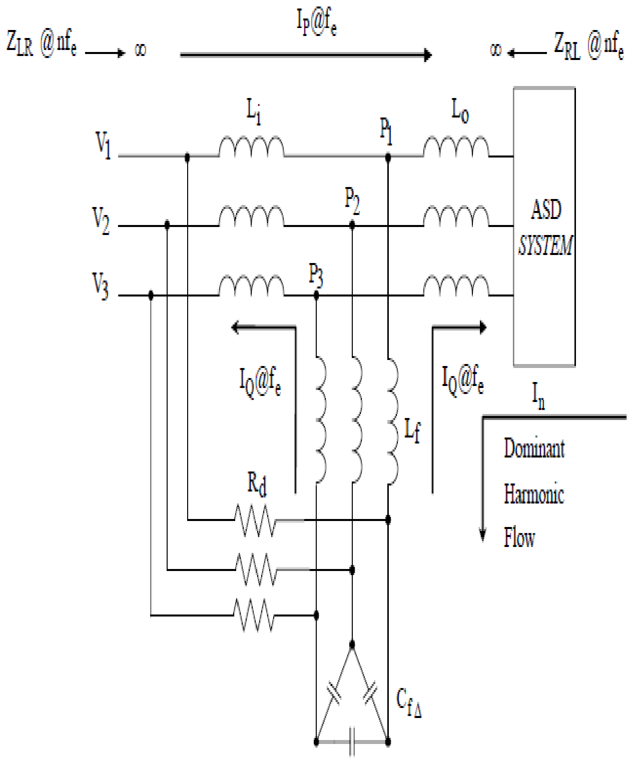

Fig. 3.1 Improved broadband filter circuit diagram.

5.0 Damping Resistor Selection Method

The IBF system along with the rectifier, involve switching transients during turn-on and turn-off of the drive. In an ASD system, the voltage and current overstresses due to the switching transients are manipulated by a DC bus pre charge circuit. Generally, this circuit is made of a resistor in parallel with a contactor (or any switch) and the switching transients can be manipulated by controlling this switch according to the DC bus voltage level. If the DC bus voltage is below a preset threshold value, the switch remains off. Otherwise, the switch is turned on and remains on throughout, bypassing the pre charge resistor. Therefore, the DC bus voltage capacitor does not experience major overvoltage stress during start-up and line voltage transients. As a result the inverter does not experience any significant overvoltage stress and the DC bus capacitor does not experience either overvoltage or over current stress, leading to economical design. Inclusion of the broadband filter in the system involves introduction of additional dynamics to the system.

An IBF can be directly connected to the ASD terminals with no additional switches. However, a three phase switch or contactor must be placed between the AC line and the IBF terminals. When turning this three-phase switch on or off, additional dynamics are excited. Considering that the precharge circuit manipulates the rectifier and drive side dynamics, the only problematic transients remaining would be on the AC side and related to the IBF components. Therefore the IBF structure and damping characteristics are important in determining the system behavior. In order to have a high efficiency system, the IBF components are designed and built with high efficiency characteristics (typically 97-99% efficient) and this implies very low damping filter structure. As a result, when enabling the input contactors, the filter experiences voltage and current overstress. Specifically, the capacitor voltage and filter output voltage can become excessively large. In order to damp the switching overvoltages, a damping resistor is necessary. In the IBF structure, as shown in Fig. 3.1, the damping resistor Rd is located across the Li and Lf total system. Its duty is to specifically damp the turn-on transient overvoltages (reduce the voltage overshoot) across the AC filter capacitors and the rectifier terminals. The choice of Rd involves two criterion, low filter capacitor voltage overshoot and low energy dissipation. While the filter energy efficiency criteria requires high energy efficiency corresponding to large Rd, the voltage overshoot criteria requires low overshoot corresponding to small Rd (high damping). Therefore, a trade-off exists between steady-state and dynamic performance.

In this paper, major effort has been spent towards obtaining a closed form analytical formula that illustrates the relation between Rd and damping ratio. The results obtained could be evaluated numerically. However, the analysis does not yield a comprehensible closed form formula. Therefore, at this stage detailed computer simulation based results will be presented and the analysis carried out will be presented in a later stage.

An ASD system with IBF structure has been considered for the detailed system simulation. Three power ratings, 5.5 kW, 55 kW, and 500 kW have been investigated. The filter parameters selected are those listed in table 3.7. Computer simulations have been conducted via Simplorer Student Version (Version 7). In the computer simulations, the inverter drive was modeled with an equivalent DC load in order to simplify the simulations. The simulation involves the start-up transient where the IBF input switch is turned-on and the filter is precharged followed by the DC bus capacitor charging. Further details of the simulation model and simulation software program will be provided in the following chapter. At this stage the damping resistor related results are presented.

6.0 Conclusion and Future Scope of Work

The first stage of the paper provided general knowledge of the common passive harmonic filtering methods and their associated circuit topologies that are utilized for ASD harmonic mitigation. This has involved a review of operating principles and design rules for three-phase AC line reactors, the DC link inductance, shunt tuned filters, and the simple low pass LC broadband filter. Weakness, strength, and performance characteristics of the various passive harmonic filtering methods have been presented. Of the various passive harmonic filtering methods presented, the low pass broadband filtering method was shown to be the only method with promising line side power quality characteristics, but at the expense of light-load operating condition over voltages. Therefore, the improved broadband filter which overcomes this weakness has been considered as the main candidate for modern power quality compliance filter.

As the low pass improved broadband filter has shown a superior performance in current harmonic mitigation for ASD application utilizing the 6-pulse diode full bridge rectifier. The topology can be adapted to different front-end rectifiers. This involves the 6-pulse thyristor full bridge rectifier applications. Other than the 6-pulse applications the topology can be also a promising method for 12-pulse front-end applications. As the current harmonic content of each rectifier structure is unique, the filter design rules and optimal parameter selection becomes an issue. Since the method developed in this paper treats the rectifier as a harmonic current source, knowledge of the rectifier harmonic current ratio is sufficient for the new design. Thus, a study involving 6 pulse thyristor rectifier, 12 pulse diode/thyristor rectifier systems should be considered and their design rules established based on the method established in this paper.

In case the utilization of the Lo filter is avoided, again the harmonic current ratio becomes different. Then the design principle leads to different filter parameters. The performance comparison between the standard method involving 4% reactor and noreactor must be considered not only from the technical point of view, but also from the cost and size optimization point of view. Thus, additional study on the subject is required. Perhaps, as the active harmonic filters remain costly and problematic, passive filtering solutions will continue finding applications. As a result high performance passive or hybrid filters must be developed to meet the increasingly strict power quality requirements of the modern technology era. Thus, new passive filter topologies involving better performance, smaller size, higher efficiency, reduced noise, and most importantly lower cost have to be developed and research in this area is a necessity of the modern power quality era.

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