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Original article

Assessing Power Quality and Harmonic Levels in Distribution Systems

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Abstract
Power distribution systems typically have tie and sectionalizing switches whose states determine the topological configuration of the network. The system configuration affects the efficiency with which the power supplied by the substation is transferred to the load. Power companies are interested in finding the most efficient configuration, the one which minimizes the real power loss of their three-phase distribution systems. The aim of this study is to obtain a new concept and analysis for odd harmonic current minimization which dominantly on three phases three wires power distribution system, and to design voltage phase angle shifting that has special phase angle to minimize fifth and seventh order harmonic current. The main purpose is to develop accurate models of power electronic devices that will be installed on future naval warships. These models used to analyze the harmonic distortion on the main electrical busses under a variety of operating conditions. The impact of harmonic mitigation techniques on an Integrated Propulsion System be analyzed. The study has studied the performance of various filter structures (with emphasis on IBF) have been discussed. Performance evaluation of the discussed filtering methods was presented and a detailed comparison provided. The steady-state performance characteristics at various operating points were in focus. Balanced and unbalanced utility grid with or without voltage harmonic distortion operating conditions were considered. The main power quality parameters (line current THDI and power factor, filter output voltage regulation) and energy efficiency attributes have been investigated. Concerning the transient conditions, the voltage overshoot at various locations of IBF based system was presented and the effectiveness of the appropriately selected damping resistor in suppressing the transients was shown.
Keywords. Power Quality, Harmonic Levels, Distribution Systems.

Introduction

Power quality has received increasing attention in recent years due to the day-by-day rise in non-linear residential loads—which draw non-sinusoidal current [1]. This is attributed to the fact that most household appliances—including televisions, Hi-Fi systems, compact fluorescent lamps (CFLs), personal computers, and various device chargers—rely on the phenomenon of rectification, which leads to the generation of harmonic distortion [2].

In the past decade or so, with the advances in communication and data processing technology, electric utility companies have become very interested in distribution automation. It is apparent that with the increasing complexity of power distribution systems, it is becoming essential to automate some tasks that have always been done manually. It has also been estimated that utilities could save as much as 10% of their annual maintenance and operating expenses by taking advantage of this technology [1]. One important area in which distribution automation is being applied is the area of network reconfiguration. Network reconfiguration refers to the closing and opening of switches in a power distribution system in order to alter the network topology, and thus the flow of power from the substation to the customers. There are two primary reasons to reconfigure a distribution network during normal operation. Depending on the current loading conditions, reconfiguration may become necessary in order to eliminate overloads on specific system components such as transformers or line sections. In this case it is known as load balancing.

Network reconfiguration in both of these cases can be classified as a minimal spanning tree problem, which is known to be an NP–complete combinatorial optimization problem. A method is needed to quickly find the network configuration which minimizes the total real power loss of the network while satisfying all of the system constraints. Several approaches have been applied to the solution of this problem with varying degrees of success. Heuristic methods [2; 3; 4] have been used successfully to find sub-optimal solutions rapidly. The genetic algorithm [5] and simulated annealing [6; 7], which require much more computation time, have been used to find optimal solutions. It seems that these methods have only been applied to relatively small, balanced, or single-phase distribution systems. Power utility companies currently need an algorithm which can be applied to their large three-phase unbalanced distribution systems.

Harmonics have existed in power systems for many years. In the past, most electrical equipment is using balance linear load. A linear load in a power system distribution is a component in which the current and voltage are perfect sinusoidal [2]. Examples of linear loads are induction motor, heaters and incandescent lamps. But the rapid increase in the electronics device technology such as diode, thyristors, and etc. cause industrial loads to become non-linear. These components are called solid state electronic or non-linear load [8, 9]. The non-linear load connected to the power system distribution will generate harmonics current and voltage [10, 11].

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Harmonics in power distribution system are current or voltage that are integer multiples of fundamental frequency. For example, if the fundamental frequency 50 Hz, then the 2-nd harmonics is 100Hz, the 3-rd is 150Hz, etc. [12]. A pure voltage or current sine wave has no distortion and no harmonics but no sinusoidal wave has distortion and harmonics. To quantify the distortion, the term total harmonics distortion (THD) is used. The THD value is the effective value of all the harmonics current added together, compared with the value of the fundamental current [6, 7]. Wave form distortion can be analyzed using Fourier analysis as a periodical oscillation at different frequency.
The harmonic current on three-phase three wires power distribution system is dominated by the 5-th and 7-th harmonics that are generated from the three phase bridge diode rectifiers [3]. The main problem of harmonics current on three phase distribution power system is harmonic resonance. The harmonic resonance is accursed in the 5-th and 7-th order harmonics frequency between power factor improvement capacitor and source inductance [1]. Two forms of resonance which must be considered. Those are series resonance and parallel resonance. For the series resonance, the total impedance at the resonance frequency reduces to the resistance component only. For the case where this component is small, high current magnitudes at the exciting frequency will flow. It may lead to large oscillating currents and consequently high harmonics voltage. For the parallel resonance, frequency the impedance is very high and when excited from a source at this frequency, a high circulating current will flow in the capacitance-inductance loop [13]. Harmonic Resonance occurs when the capacitor reactance and the system reactance are equal. These currents will result in greater voltage distortion. This provides a higher voltage across the capacitor and potentially harmful currents through all capacitor equipment. Harmonic resonance may occur at any frequency but the 5-th, 7-th are the frequencies with most concerned [14, 15, 16]. Some indicators of resonance are overheating, frequent circuit breaker tripping, unexplained fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.
In power distribution systems with more than 15%-20% of harmonic loads, a harmonic survey should be performed to indicate potential problem areas [17]. Readings taken over changing load conditions at potential capacitor locations are most useful in determining the types of systems best employed to accomplish the ultimate harmonic suppression, power factor improvement, KVA reduction and other goals. Today, a number of methods have been proposed to address this phenomenon. One conventional method is the application of LC passive filter. However, LC passive filter has disadvantages: The designing form is large and weight to filter low frequency harmonic current order. The LC filter which to filter harmonic current needs specific value of LC for each order harmonic. Beside this, The LC filter has a problem formulation due to the system impedance variation and resonance condition. The other method in reducing harmonic is Active Power Filter (AFP). The active power filter is a PWM inverter current source. Therefore, it is very difficult used for high capacity and more expensive. The other disadvantage of PWM inverter is that it generates high order harmonic current which can distorted the telecommunication systems, audio and video [5].
In this thesis explains the total harmonic minimization in three-phase three wires power distribution system. The method of THDi minimization is used voltage phase angle shifting in branch loads system. With voltage angle phase shifting in branch loads as well as the harmonic current component phase angle were occurred. The value and direction of harmonic current phase angle is depended order and phase sequence. The specified voltage phase angle shifting can obtain the specified 5-th and 7-th harmonic current component phase angle shifting in branch loads. It is shifted angle phase by 300. Due to specified harmonic current component phase angle shifting cause the 5-th and 7-th harmonic current component in two branch loads is opposite. Therefore, the superposition of 5-th and 7-th harmonic current component in branch loads will be canceled. Hence, the line system did not contain 5-th and 7-th harmonic current component. It mean that the THDi can be minimized. The purpose of this study is to develop accurate models of power electronic devices that will be installed on future naval warships. These models will be used to analyze the harmonic distortion on the main electrical busses under a variety of operating conditions. The impact of harmonic mitigation techniques on an Integrated Propulsion System will also be analyzed.

Literature review

Current harmonics and problems

Authors in [18] presented those non-linear loads such as fluorescent lighting with electronic ballasts, switch mode power supply, single phase SMPS, battery chargers, rectifiers, inverters, three phase power converter fed drives, arc furnaces, arc welding, discharge lighting and saturable reactors etc. will produce current harmonics in the power system leading to current and voltage waveform distortion. All these loads draw the non-sinusoidal currents resulting in current harmonics and are injected back into the supply system through the point of common coupling (PCC) [18]. Authors in [19] explained the effect of current harmonics on the performance different power system equipment such as s capacitors, transformers, motors, energy and demand metering equipment causing additional losses, overheating and overloading and interference with telecommunication lines. Certain harmonics, like the fifth and seventh, create a rotating magnetic field that spins in the opposite direction of the fundamental harmonic, leading to heating and mechanical oscillations in motor systems [3].

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Source of harmonics

The main source of the harmonics is any non-linear loads that produce the voltage harmonics and current harmonics. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sine wave. So, non-linear device is one in which the current is not proportional to the applied voltage. Some examples of common sources of power distribution system harmonics cause serious problems are [4, 20, 21]:

1. Fluorescent lighting
2. Computer switch mode power supplies
3. Static VAR compensators
4. Variable frequency motor drives (VFD)
5. DC-DC converters
6. Inverters
7. Television power supplies.

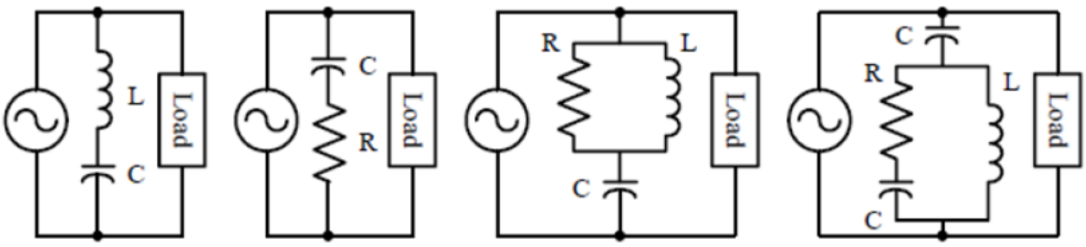
The effect of current distortion on power distribution systems can be serious, primarily because of the increased current flowing in the system. In other words, because the harmonic current doesn't deliver any power, its presence simply uses up system capacity and reduces the number of loads that can be powered [20]. Harmonic current occur in a facility's electrical system can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, tripping of circuit breakers, and solid-state component breakdown. The cost of these problems can be enormous. Harmonic currents also increase heat losses in transformers and wiring. Since transformer impedance is frequency dependent, increasing with harmonic number, the impedance at the 5th harmonic is five times that of the fundamental frequency. So, each ampere of 5th harmonic current causes five times as much heating as an ampere of fundamental current [21, 22].

Harmonic mitigation in low voltage power distribution system

Harmonic distortion in a power distribution system can be suppressed through three basic approaches namely:
(1) Passive filtering
(2) Active power filtering and
(3) Hybrid active power filtering.

Passive filtering of harmonics

Gonzalez, D. A., et.al [13] proposed shunt passive filters for harmonic mitigation in power system. Shunt passive filters are configured with inductance, capacitance and resistance elements and tuned to control harmonics. Common types of passive filters and their configurations are shown in Fig. 1.



Single-tuned | First-order High-pass | Second-order High-pass | Third-order High-pass

Fig. 1. Common types of passive filters and their configurations.

Shunt passive filters are advantageous over series compensators as they will compensate for harmonics as well as reactive power, in addition they will not carry large currents hence associated losses are less. Authors in [23] proposed high pass filter for notch reduction in a power distribution system having large electronic loads. Notch filter will bypass the high frequency harmonics to ground. Single tuned filters are more effective to suppress harmonics of selected frequency. The transfer function approach of passive filter design is presented by [8]. The first-order filter, which is characterized by large power losses at fundamental frequency but it is simple to implement. The second-order HPF provides good filtering action and fundamental frequency losses are less. The filtering performance of the third-order HPF is superior to that of the second-order HPF. However, it is found that the third-order HPF is not commonly used for low-voltage or medium-voltage applications since the economic, complexity, and reliability factors do not justify them. Although simple and least

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expensive, the passive filter inherits several shortcomings. The filter components are very bulky because the harmonics that need to be suppressed are usually of the low order according to [9]. Furthermore, the compensation characteristics of these filters are influenced by the source impedance and filter design is heavily dependent on the power system in which it is connected. The passive filter is also known to cause resonance, thus affecting the stability of the power distribution systems. Frequency variation of the power distribution system and tolerances in components values affect the filtering characteristics. The size of the components becomes impractical if the frequency variation is large [9].

Active filtering of harmonics

The progress in power electronics had spurred interest in active power filter (APF) for harmonic distortion mitigation. Authors in [10] discussed about harmonic producing loads and mitigation methods using passive filters, active filters hybrid filters. The hybrid filter topologies include series active filter and shunt passive filter, shunt active filter connected in series with shunt passive filter. The basic principle of APF is to produce specific harmonic current components that cancel the harmonic current components caused by the nonlinear load. Fig. 2 shows the components of a typical APF system and their connections.

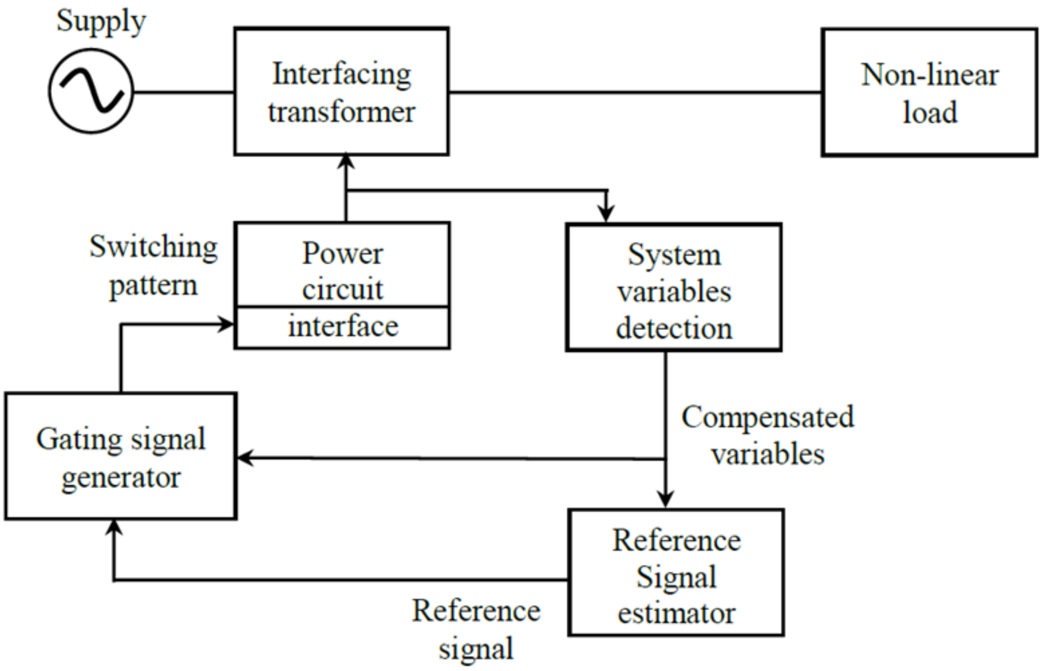

Fig. 2 Generalized block diagram for APF.

The information regarding the harmonic currents and other system variables are passed to the compensation current/voltage reference signal estimator. The compensation reference signal from the estimator drives the overall system controller. This in turn provides the control for the gating signal generator. The output of the gating signal generator controls the power circuit. Finally, the power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations depending on the interfacing transformer used.

APFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APF performances are independent of the power distribution system properties [10]. On the other hand, APFs have some drawbacks. APF necessitates fast switching of high currents in the power circuit resulting high frequency noise that may cause an electromagnetic interference (EMI) in the power distribution systems [10]. Paper [11] proposed the classification of active filters based on their objectives, system configuration, power circuits and control strategy. APF can be mainly connected in three circuit configurations, namely shunt APF, series APF and hybrid APF.

Advantages of active harmonic filter

1. Widely compensated harmonic spectrum
2. Only one filter needed to eliminate all the unwanted harmonics
3. Improved stability of the power system due to the lack of parallel resonance

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4. Its performance is dynamic and take into account the changes in load
5. It may also be programmed to eliminate specific number of harmonics
6. They may also be programmed to eliminate harmonics with or without compensation of reactive power

Harmonics

Harmonics are one of the major concerns in a power system. Harmonics cause distortion in current and voltage waveforms resulting into deterioration of the power system. The first step for harmonic analysis is the harmonics from non-linear loads. The results of such analysis are complex. Over many years, much importance is given to the methods of analysis and control of harmonics. Harmonics present in power system also has non-integer multiples of the fundamental frequency and have aperiodic waveform. The harmonics are generated in a power system from two distinct types of loads.

First category of loads are described as linear loads. The linear time-invariant loads are characterized such that application of sinusoidal voltage results in sinusoidal flow of current. A constant steady-impedance is displayed from these loads during the applied sinusoidal voltage. As the voltage and current are directly proportional to each other, if voltage is increased it will also result into increase in the current. An example of such a load is incandescent lighting. Even if the flux wave in air gap of rotating machine is not sinusoidal, under normal loading conditions transformers and rotation machines pretty much meet this definition. Also, in a transformer the current contains odd and even harmonics including a dc component. More and more use of magnetic circuits over a period of time may get saturated and result into generation of harmonics. In power systems, synchronous generators produce sinusoidal voltages and the loads draw sinusoidal currents. In this case, the harmonic distortion is produced because of the linear load types for sinusoidal voltage is small. Non-linear loads are considered as the second category of loads. The application of sinusoidal voltage does not result in a sinusoidal flow applied sinusoidal voltage for a non-linear device. The non-linear loads draw a current that may be discontinuous. Harmonic current is isolated by using harmonic filters in order to protect the electrical equipment from getting damaged due to harmonic voltage distortion. They can also be used to improve the power factor. The harmful and damaging effects of harmonic distortion can be evident in many different ways such as electronics miss-timings, increased heating effect in electrical equipment, capacitor overloads, etc. There can be two types of filters that are used in order to reduce the harmonic distortion i.e. the active filters and the passive filters. Active harmonic filters are electronic devices that eliminate the undesirable harmonics on the network by inserting negative harmonics into the network. The active filters are normally available for low voltage networks. The active filters consist of active components such as IGBT-transistors and eliminate many different harmonic frequencies. The signal types can be single phase AC, three phase AC. On the other hand, passive harmonic filters consist of passive components such as resistors, inductors and capacitors. Unlike the active filters which are used only for low voltages, the passive filters are commonly used and are available for different voltage levels [13,2].

Active Harmonic Filter

As explained earlier, the active harmonic filters are used for low voltages where reactive power requirement is low. The way this filter works is, the output load with the voltage waveform is obtained by boosting the voltage throughout each half cycle by the filter. The voltage which is thus produced tends to rectifiers in the power supply to gain current. The duty cycle and power factor are thus improved. Depending on the active harmonic filter used, the output distortion is reduced. Also, current that is produced due to load is monitored by the harmonic filter and generates a waveform which coincides with the exact shape of the nonlinear portion of the load current [2, 23].

Passive Harmonic Filter

As shown before, the passive harmonic filters are such that they are used for different voltage levels. In case of passive harmonic filters, the harmonics are reduced by using series or parallel resonant filters. The way these passive harmonic filters works is, a filter connected in parallel with the load and in series with inductance and capacitance is a current acceptor. A current acceptor is a parallel filter which is in parallel with the load and is in series with the inductance and capacitance. The filter which is near the resonant frequency of the parallel array provides maximum attenuation. The filter passes as much current as the harmonic voltage nears the filter resonant point. The passive filters thus eliminate the harmonics. If the individual load requirement is more than that of the input load, the harmonic current should be eliminated. A capacitor in series with an inductance is a passive filter. The reduced harmonic frequency must be equal to the resonant frequency of the circuit. The impedance of the network and the low impedance of the filter thus eliminate the harmonic current [2,23].

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Results and Conclusion

Simulation and Calculations

When studying the effects of the utility grid voltage distortion on the filter performance, a 3% THD_V is considered for all filtering topologies investigated. In the study it is assumed that the voltage harmonics (V_n values) are 2.2% 5th, 1.3% 7th, 1.1% 11th, 0.9% 13th all with respect to the fundamental component. These ratios are selected such that the lower frequency components have larger magnitude as it is normally the case in practice. Utility supply of 380V line-to-line voltage and 50Hz frequency is considered. The supply source impedance parameters for the various power ratings can be considered.

The investigation involves three power ratings, low power, medium power, and high-power general-purpose ASDs with 5.5 kW, 55 kW, and 500 kW ratings respectively. The series inductor filter type filtering study is done with 3% and 6% both. The tuned filter approach involves the 5th and 7th filters.

In the computer simulations the rectifier of the ASD system is modeled with "system level" diodes (reverse recovery effect and switching dynamics neglected). The filter and utility grid are fully modeled with accuracy (including the parasitic and distortion). The inverter side of the ASD system modeled with an equivalent resistor and switch. Since the DC bus capacitor decouples the PWM dynamics of the drive from the rectifier side, this approximation is highly acceptable and does not result in loss of accuracy in filter performance prediction. Based on the data of the recent industrial products, the ASD system DC link capacitor, precharge resistor, and load parameters are given in Table 1.

Table 1. ASD system parameters for various power ratings

P_R (kW)	5.5	55	500
L_{dc} (2%) mH	1.50	0.152	0.017
Rprecharge (Ω)	20	2.0	0.2
C_{dc} (mF)	1.0	10	90

For the purpose of modeling, a graphic computer simulation package program Ansoft-Simplorer (student 7th version, SV7) has been utilized. The program is a graphic window based (pick and place) power electronic circuit simulator. The computer simulation software involves a circuit schematic diagram window, a graphic view window (view file), and the Day-postprocessor window. In the schematic window the circuit is drawn and simulation parameters are given. The graphic window displays the simulation waveforms as in an oscilloscope. The Day postprocessor window provides data processing tools for the purpose of harmonic spectrum, THD, etc. calculation.

In the computer simulation the integration method is trapezoidal integration method. Other related parameters are shown in Fig. 3. The shown step size is selected low for high accuracy. The simulation end time is selected such that the modeled system reaches its steady-state conditions. All database results for the selected outputs are saved at the steady-state period (last two cycles). Therefore, the Day-postprocessor processes the saved data and calculates results at steady-state conditions and all transient results are eliminated for high accuracy results. However, for transient analysis the focus is within the first few cycles. The circuit simulator is based on a modified nodal approach. The trapezoidal algorithm is applied for the solution of the differential equation system. The solution of nonlinear equations is done by the Newton-Raphson method. The calculation of equation systems, linearization in the operating point, takes place by means of LU factorization after applying Gauss method.

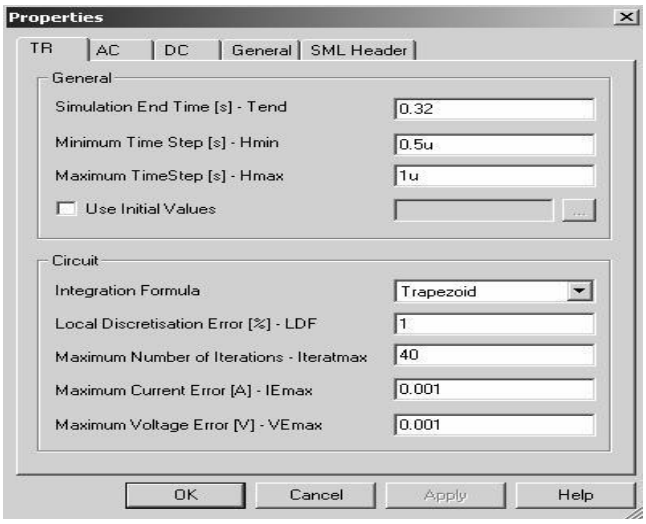

Fig. 3. Simulator integration method and its computational parameters.

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AC Line Reactor Filter Based ASD System Simulations

In this section, performance analysis of three-phase 3% and 6% AC line reactor filter-based ASD system under balanced and distorted utility (with 3% THD_V) is presented. Simulation current and voltage simulation waveforms are illustrated and analyzed. The AC line reactors are combined with a 2% DC link inductor to increase the effectiveness of the filtering method. The parameter values of the AC line reactances utilized and their equivalent series resistances for the 5.5 kW, 55 kW, and 500 kW power ratings are shown in Table 2. The table also contains the ASD system DC side equivalent load resistor (R_{dc}) information. Since different AC line reactors result in different DC bus voltage levels, constant load power implies different R_{dc} values. These parameters are implemented in the simulation circuit, shown in Fig. 4, for all the power ratings considered.

Table 2. Series AC line reactor filter parameters along with the load resistance values

AC Line Reactors	5.5 kW	55 kW	500 kW
L_{ac} (3.0%) mH	2.30	0.229	0.026
R_{ESR} (mΩ)	7.1	0.71	0.079
R_{dc} (Ω)	45	4.5	0.495
L_{ac} (6.0%) mH	4.60	0.458	0.051
L_{ac} (6.0%) mH	14.3	1.43	0.16
R_{dc} (Ω)	43.5	4.35	0.483

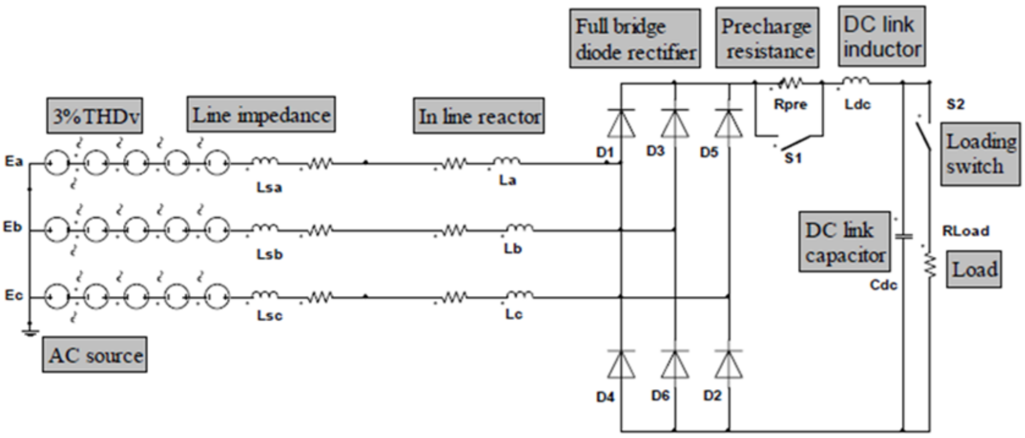

Fig. 4 Simulation circuit of the ASD system that utilizes AC line reactor and DC link inductor filter.

Full-Load Simulations of 5.5kW Rated System

In this section, the simulation results and waveforms for 3% and 6% AC line reactors (Table 2) and ASD system (Table 1), for 5.5kW ratings are presented. For the 55kW and 500kW rated systems, only the basic results will be summarized due to limited space and significant similarity of the results with the 5.5kW case. The full-load line current and supply voltage simulation waveforms for both 3% and 6% AC line reactors filtering methods for the 5.5kW ASD system are shown in Fig. 5 and Fig. 6, respectively. In the figure, the current waveform is up-scaled by 10 (implying the actual current is 10 times smaller than that is shown in the figure). The full-load line current has 36% and 29% THDI values for the 3% and 6% AC line reactors, respectively. The line power factor is 0.92 lagging for both.

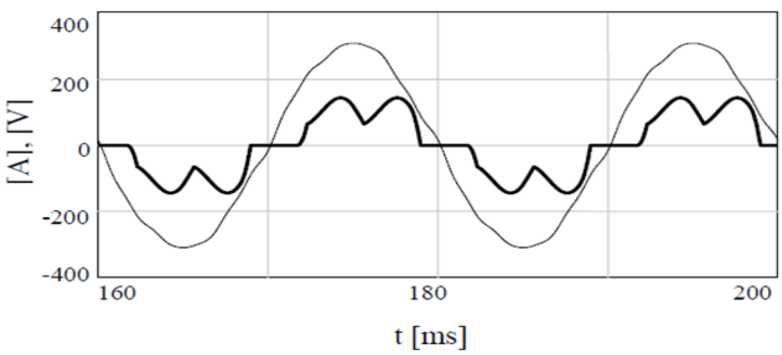

Fig. 5 Full-load line current (bold) and supply voltage simulation waveforms for 5.5kW ASD system utilizing 3% L_{ac} and 2% L_{dc} filter (current scale: 10x).

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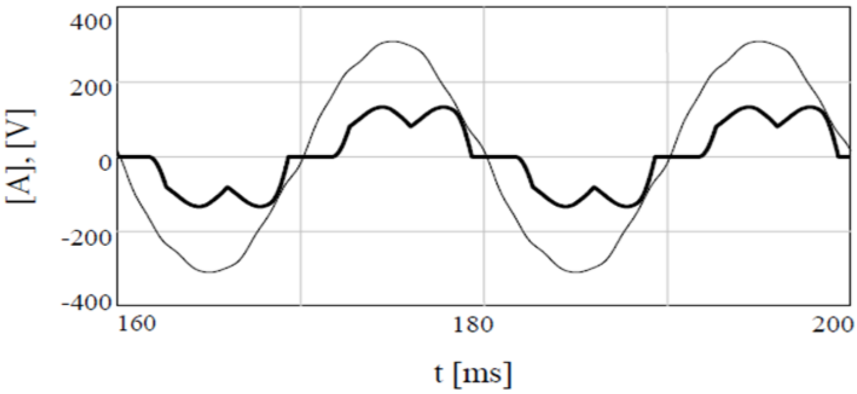

Fig. 6 Full-load line current (bold) and supply voltage simulation waveforms for 5.5kW ASD system utilizing 6% L_{ac} and 2% L_{dc} filter (current scale: 10x).

The rated load DC voltage and current simulation waveforms are shown in Fig. 7 and Fig. 8. It is seen that the 3% AC line reactor filter results in a 502V DC rated output voltage value while the 6% AC line reactor filter results in a lower value of 492V DC Rated output voltage. This is due to the larger voltage drop across the 6% reactance.

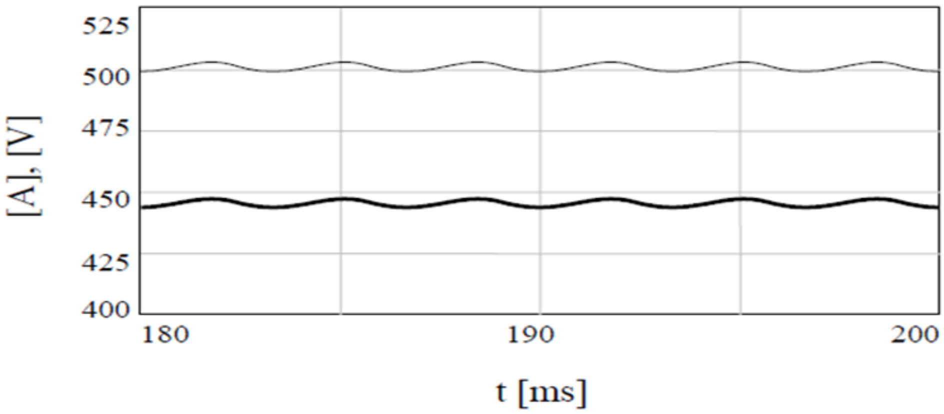

Fig. 7 Full-load DC load current (bold) and voltage simulation waveforms for 5.5kW ASD system utilizing 3% L_{ac} and 2% L_{dc} filter (current scale: 40x)

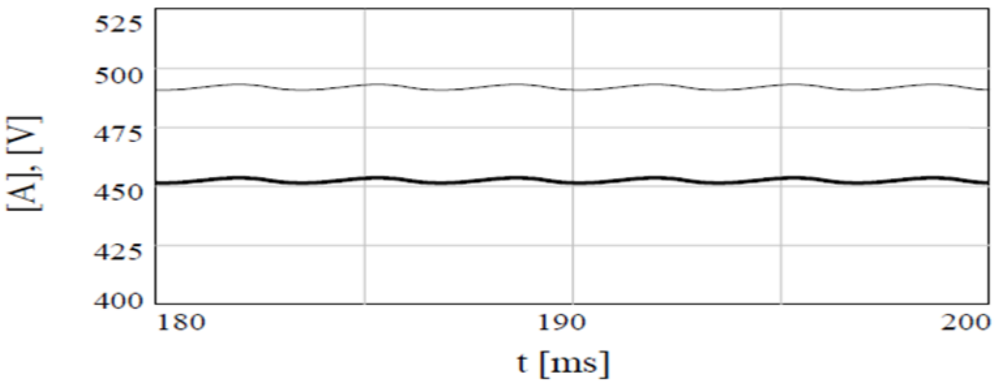

Fig. 8 Full-load DC load current (bold) and voltage simulation waveforms for 5.5kW ASD system utilizing 6% L_{ac} and 2% L_{dc} filter (current scale: 40x).

From the above simulation results, it is seen that the reactor filter topology has poor performance at full-load with high line current THD_I values (> 29%) and low line power factor values (0.92). It can be noticed that combining the 2% L_{dc} link inductor slightly improves the line current THD_I values compared with the no DC link inductor case. However, the improvement is marginal and for both AC line reactor cases, the line THD_I values are high and do not comply with the modern power quality standards. Further, the topology causes a voltage reduction in the DC output voltage at full-load. The amount of DC output voltage reduction in both cases is consistent with Equation 2.7 that estimates the DC voltage reduction.

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Table 3 shows the full-load performance for the selected power ratings for both 3% and 6% AC line reactor combined with the 2% L_{dc} inductance filter. The same conclusions as for the 5.5kW rating can be made for the higher ratings. AC line reactance-based filtering (with or without the DC link inductor filtering) is insufficient in terms of modern power quality compliance.

Table 3. Full-load performance of 3% and 6% AC line reactor filter for various power ratings

	3% AC Line Reactor			**6% AC Line Reactor**		
P_R (kW)	5.5	55	500	5.5	55	500
THD_I	36	36	35	29	29	29
PF	0.92	0.92	0.92	0.92	0.93	0.93
V_{dc} (V)	502	501	499	492	492	491

Tuned Filter Design and Tuned Filter Based ASD System Simulations

Tuned Filter Design

As we know, practically single tuned filters are utilized at increasing power levels and the tuned filters are designed for the most dominant harmonics of the rectifier (typically 5 or 5&7). For high performance, a filtering system with the 5th and 7th harmonic shunt filters with added 6% AC input reactor (L_i) and 3% AC rectifier output reactor (L_o) that forms a T-shape topology is designed. In the design of each single tuned filter (5th and 7th), the filter capacitors are sized to also provide full fundamental frequency reactive power compensation (Q_F). This filter reactive power compensation is calculated by

$$Q_F = Q_R - Q_L \quad (1)$$

where Q_R is the rated fundamental frequency reactive power the rectifier takes and Q_L is the rated fundamental frequency reactive power of the line. Both reactive power quantities are calculated based on the rated DC output power P_{dc} and the displacement angles between the phase voltage and line current fundamental components at both sides (rectifier and line) as follows:

$$Q_F = P_{dc}(\tan\varphi_R - \tan\varphi_L) \quad (2)$$

where φ_R and φ_L are the rectifier and utility line displacement angles, respectively. The rectifier rated displacement angle φ_R for the diode bridge rectifier is given by

$$\varphi_R = u/2 \quad (3)$$

where u is the rectifier overlap angle due to current commutation between outgoing and incoming conducting diodes. It is given by

$$\cos u = 1 - \frac{2\omega_e L_{ac} I_{dc}}{V_{LL}\sqrt{2}} \quad (4)$$

where L_{ac} is the total AC line reactors utilized (6% and 3%), I_{dc} is the rated DC load current, V_{LL} is the line-to-line voltage and ω_e is the fundamental electrical angular velocity.

For calculated φ_R and assumed φ_L value to be 0° (unity power factor design criteria), the total demanded fundamental reactive power to be supplied by both shunt single filters (Q_F) are calculated. The 5th filter capacitor is assumed to supply 55% of Q_F while the 7th filter capacitor is assumed to supply 45% of Q_F (could be selected differently). At the fundamental frequency, neglecting the filter reactors (because the reactor impedance is negligible), the tuned filter is purely capacitive. Therefore, each filter capacitor is sized by

$$C_x = \frac{Q_x}{\omega_e V_{LL}^2} \quad (5)$$

where Q_x is the individual reactive power demand for the corresponding capacitor C_x. The calculated capacitance values assume star connection. Since in practice generally Δ configuration is utilized, these values are converted to Δ connected capacitance values (by dividing by 3) as shown in Table 4.

After sizing the 5th and 7th filter capacitors, each filter reactor is calculated for the corresponding harmonic frequency (250Hz and 350Hz for 50 Hz fundamental frequency) value with 4% detuning factor. The obtained filter parameters and the ASD system DC load equivalent resistance value for the 5.5 kW, 55 kW, and 500 kW ratings are shown in Table 4.4. These parameters are implemented in the simulation circuit, shown in Fig. 9, for all power ratings considered. To improve the performance of the method a 2% DC link inductor is added (as included before in the AC line reactor filter case).

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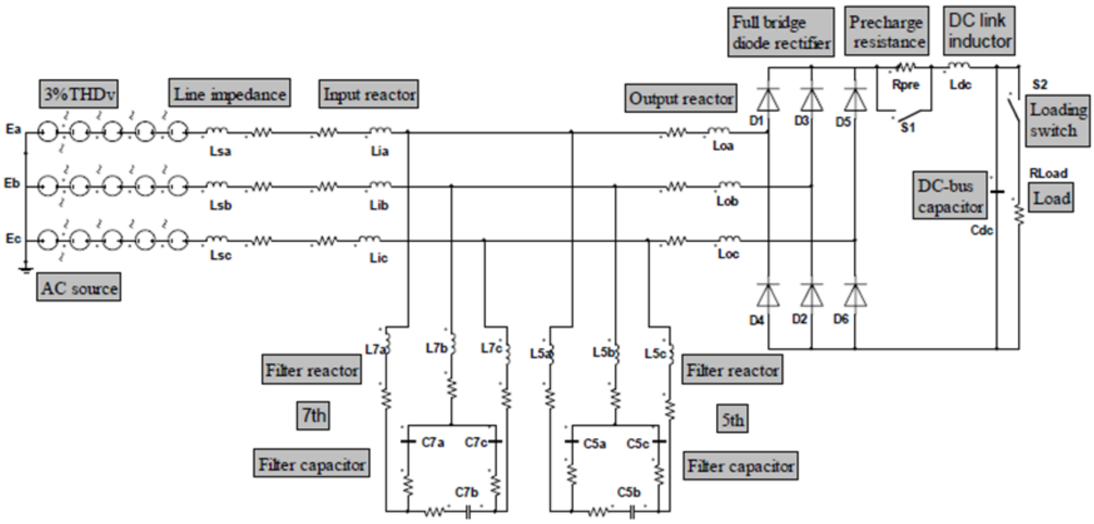

Fig. 9 Simulation circuit of the ASD system that utilizes T-shape 5th and 7th single tuned filters and DC link inductor filter.

Table 4. Tuned filter parameters for various power ratings

P_R(kW)	5.5	55	500
L_i (6.0%) mH	4.60	0.458	0.051
R_{ESR} (mΩ)	14.3	1.43	0.16
L_o (3.0%) mH	2.30	0.229	0.026
R_{ESR} (mΩ)	7.1	0.71	0.079
L_5 (mH)	29.6	3.00	0.332
R_{ESR} (mΩ)	400	40	4.4
$C_{5\Delta}$ (μF)	4.94	49.47	441.7
R_{ESR} (mΩ)	80*	8.0	0.9
L_7 (mH)	18.5	1.80	0.207
R_{ESR} (mΩ)	210	21	2.3
$C_{7\Delta}$ (μF)	4.04	40.47	361.4
R_{ESR} (mΩ)	72*	7.2	0.8
R_{dc} (Ω)	45	4.5	0.5

Full-Load Simulations of 5.5 kW Rated System

In this section, the simulation results and waveforms for the T-shape 5th and 7th single tuned filters (Table 4) and ASD system (Table 1), for 5.5kW ratings are presented. In practice low power rating systems such as the presently discussed 5.5 kW rated system do not utilize the tuned filter approach, in particular the utilization of both the 5th and 7th filters at the same time is prohibitive from the cost perspective. At such power ratings, if necessary, typically the 5th harmonic filter is utilized and 7th is not. However, for performance evaluation and comparison studies done in this thesis, as the METU University laboratory has limited power capacity, and the project budget is limited, in this study only 5.5 kW rated system could be built and tested. For this reason, the performance for this rating system will also be thoroughly investigated throughout this thesis. The full-load line and rectifier current simulation waveforms are shown in Fig. 10. The topology reduces the rectifier current 30% THD_I value to the line current 13% THD_I value at full-load. The full-load line current and supply voltage simulation waveforms are shown in Fig. 11. The line power factor is near unity with 0.99 lagging value.

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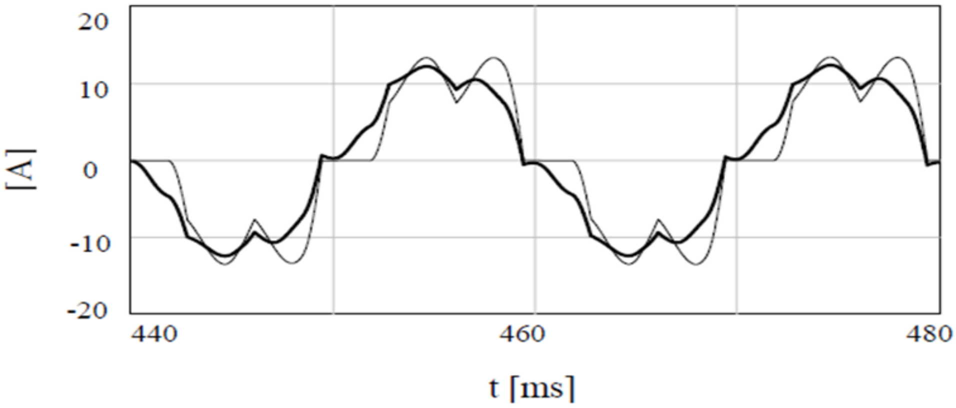

Fig. 10 Full-load line (bold) and rectifier current simulation waveforms for 5.5kW ASD system utilizing 5th and 7th tuned and 2% L_{dc} filter.

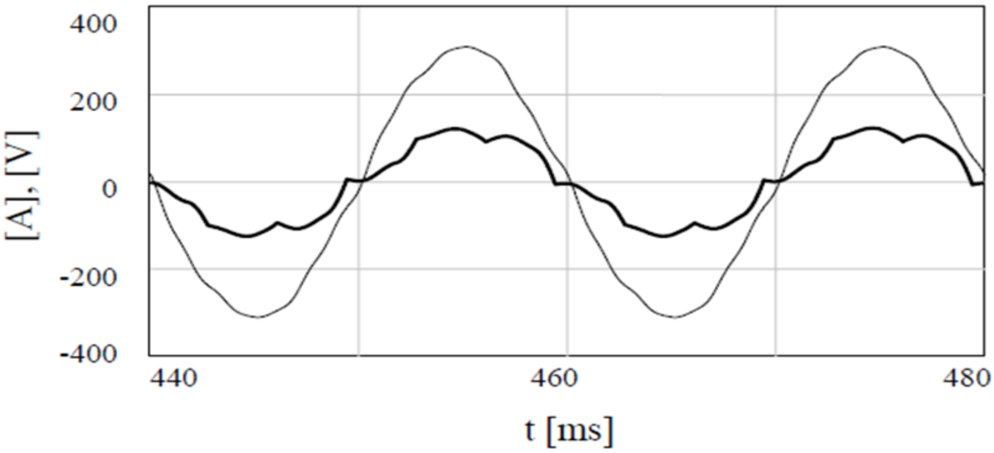

Fig. 11 Full-load line current (bold) and supply voltage simulation waveforms for 5.5kW ASD system (current scale: 10x).

Filter Performance Comparisons

This section presents the performance comparison of various passive harmonic filters for three-phase diode rectifier front-end type adjustable speed drives. The comparison is based on the simulation results obtained. The filter full-load performance characteristics are listed in Table 5. The table indicates that the improved broadband filter THD_I and power factor performance is superior to the other filter configurations. The DC bus voltage of IBF is slightly higher (4%) than the alternatives and this is not considered as a drawback.

Only the tuned filter performance is comparable to IBF. However, even the tuned filter has about 3% higher THD_I therefore the performance difference is significant. Therefore, IBF provides higher input power quality than the other passive filtering methods. At the output it also provides stable output voltage with high voltage regulation.

As Table 5 indicates, the efficiency of the IBF based system is comparable to the tuned filter-based system due to the fact that both filters involve similar number of components with similar ratings. The 3% and 6% AC line reactors have higher efficiency, due to the minimal component count, however at the expense of poor overall performance.

Table 5. Full-load performance of various filters for 5.5-500 kW ASD systems*

Filter Type	3% line **Reactor**	6% line **Reactor**	Tuned Filter	IBF
Full-Load InPut	36	29	12-13	9.2-9.4
Input power Factor	0.92 (lag.)	0.93 (lag.)	0.99 (lag.)	0.98 (lead.)
Full-Load DC Voltage (V)	499-502	491-492	495-497	520-521
Efficiency	99.96-99.97	99.39-99.94	98.8-99.4	99.0-99.2

* Supply THD_V = 3%.

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Conclusion

In conclusion, the performance of various filter structures (with emphasis on IBF) have been discussed. Performance evaluation of the discussed filtering methods was presented and a detailed comparison provided. The steady-state performance characteristics at various operating points were in focus. Balanced and unbalanced utility grid with or without voltage harmonic distortion operating conditions were considered. The main power quality parameters (line current THDI and power factor, filter output voltage regulation) and energy efficiency attributes have been investigated. Concerning the transient conditions, the voltage overshoot at various locations of IBF based system was presented and the effectiveness of the appropriately selected damping resistor in suppressing the transients was shown.

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