Comparison of Thyristor-Rectifier with Hybrid Filter and Chopper-Rectifier for High-Power, High-Current Application

Jitendra Solanki[1], Norbert Fröhleke[1], Joachim Böcker[1], Peter Wallmeier[2]
[1]Power Electronics and Electrical Drives, University of Paderborn, Paderborn, Germany.
Email: solanki@lea.upb.de
[2]AEG Power Solutions GmbH, Belecke-Warstein, Germany

Abstract

This paper presents a comparison of two rectifier-systems for high-power, high-current application. The most popular choice of circuit topology for this type of application is a multi-pulse thyristor rectifier. Active or passive filters are added to the thyristor rectifier for improving the power factor and reducing current THD. Other type of solution comprises of a multi-pulse diode rectifier followed by a multi-phase DC chopper (chopper-rectifier). A comprehensive system level approach is chosen for comparison of 12-pulse thyristor rectifier with a hybrid filter and 12-pulse diode rectifier with a multi-phase DC chopper. Comparison is carried out in terms of system performance, efficiency, size and cost for an industrial load with given system specifications.

1. Introduction

High current rectifiers are required in many industrial processes, especially in metal and chemical industries [1]-[6]. Chemical electrolysis is used in metal refining (from impure stock) and metal winning (from ore) [2]. Hydrogen, chlorine, sodium hydroxide, sodium chlorate, oxygen and adiponitrile production processes also utilize electrolysis [3]. Typical voltage requirements for these processes are of the order of few hundred volts at several kA current [1], [6].

A multi-pulse thyristor rectifier is the most popular choice for high power high current rectification [1]. However, due to variable output voltage requirement, high reactive component in the input current leads to very poor power factor at higher firing angles. This variable reactive current component needs to be compensated and for this a hybrid compensator is proposed in [6]. The configuration uses 11th harmonic filter for harmonic compensation and average reactive power compensation. A voltage source converter (VSC) based DSTATCOM is used for variable reactive power compensation. The system provides advantages in terms of DSTACOM rating reduction and loss minimization. Another option used in this kind of application is a multi-pulse diode rectifier followed by a dc chopper [1], [7], [8]. The chopper based system provides distinct advantages over the thyristor based system in terms of constant high power factor, low current harmonics, better control over load current and voltage, lower output filter requirement and simpler control [1]. To improve the THD and power factor further a passive harmonic filter with appropriate reactive power rating can be added at the input stage.

The qualitative comparison of the thyristor rectifier and the chopper-rectifier has been discussed in literature [1], [4], [5]. However, a comprehensive and quantitative comparison for an industrial load with a precise set of specifications has not been discussed.

This paper compares the above stated options, 12-pulse thyristor rectifier with hybrid filter (TRHF) and a 12-pulse diode rectifier with passive filter followed by a multi-phase chopper (CRPF). The performance of these rectifier systems is evaluated for supplying power to a high-power high-current industrial load with certain input and output power quality specifications. Systems are designed to meet a set of performance criterion and then compared in terms of efficiency, size and cost.

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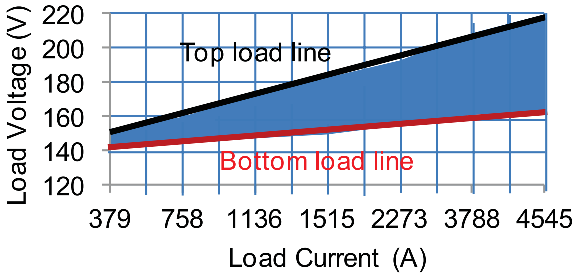


Fig. 1. Load curve

Table I: System specifications

Input voltage	400V
Input frequency	50 Hz
Maximum output voltage	220 V
Maximum output current	4545 A
Output voltage ripple	2 %
Input power factor	>0.98 (at 30-100 % current)
Input current THD	<5 % (at 30-100 % current)

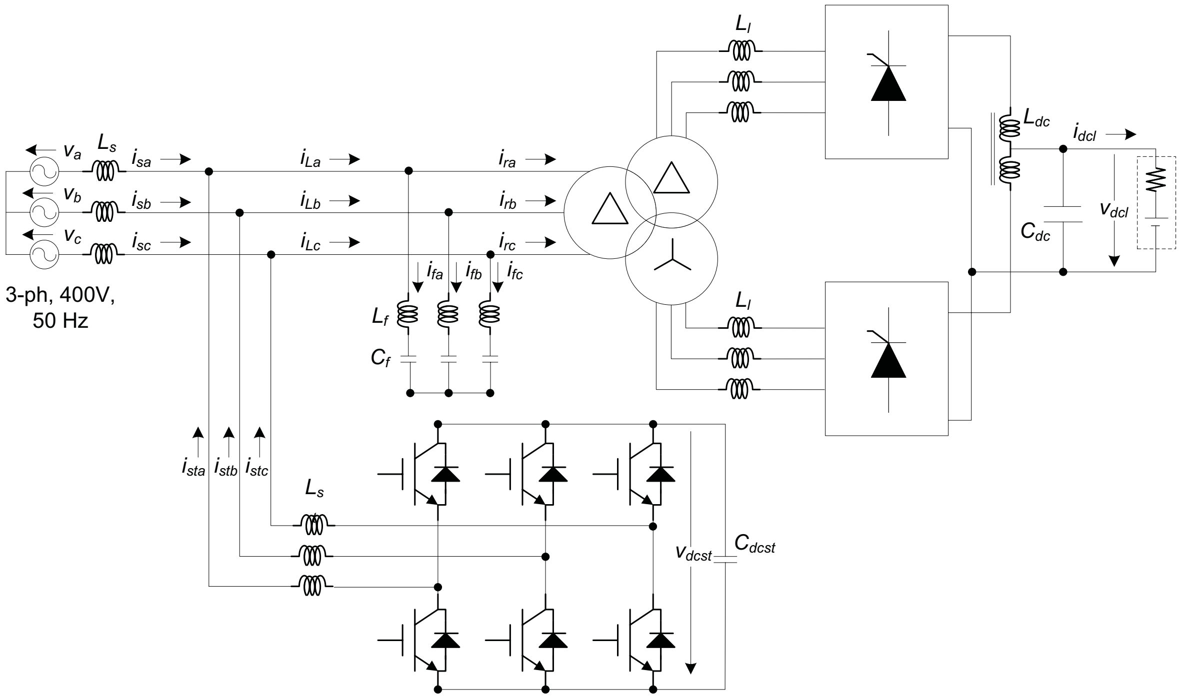


Fig. 2. Basic block diagram of 12-pulse rectifier, passive filter and DSTATCOM (TRHF).

2. System Specifications

Fig.1 shows a typical load curve of a 1 MW high-current industrial load. The control variable is the electric current. Load voltage depends on the open circuit voltage and internal resistance. Internal resistance varies with physical parameters such as temperature and age of the load. Variation of the load current is from 0 to 4545 A and the load voltage varies from 142 V to 220 V. Linearization of load profile at top and bottom boundary lines is carried out and load voltages for top and bottom curves can be represented as a function of load current respectively as:

$$v_{dcl} = v_{dcl0T} + r_{lT} i_{dcl} \tag{1}$$

$$v_{dcl} = v_{dcl0B} + r_{lB} i_{dcl} \tag{2}$$

where v_{dcl}, v_{dcl0T}, v_{dcl0B}, i_{dcl}, r_{lT} and r_{lB} are the load voltage, open circuit load voltage at top and bottom load lines, load current, load resistance along top and bottom load lines respectively. Values of v_{dcl0T} and v_{dcl0B} are 150 V and 142 V respectively and r_{lT} and r_{lB} are 15.4 mΩ and 4.84 mΩ respectively.

The requirements/specifications of the equipment are given in Table I and design of the rectifiers are carried out according to these system requirements.

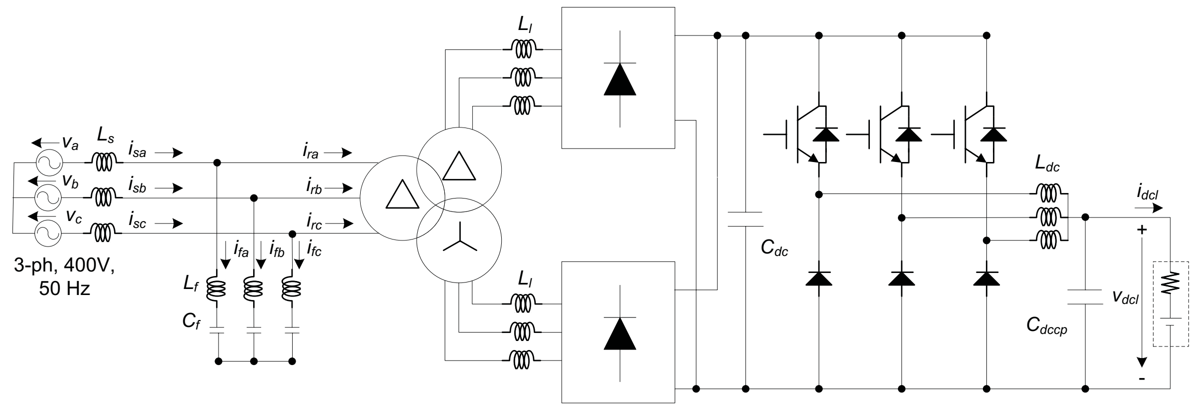


Fig. 3. Basic block diagram of 12-pulse diode rectifier with three-phase chopper and 11th harmonic input passive filter (CRPF).

Table II: System Parameters

TRHF	CRPF
Source: 3-ph, 400 V, 50 Hz, L_s=10 µH Transformer: 1000 kVA, ddy11, V_{pri}=400 V, V_{sec}=172 V, L_l=6 % Rectifier: L_{dc}=45.63 µH, C_{dc} =8000 µF (FFLI6B1007K by AVX Corp. 8 in parallel), Thyristor: I_{Tav}=757 A, TZ800N12KOF by Infineon Inc. (2 in parallel) DSTATCOM: 170 kvar, f_s=5 kHz, L_{st}=0.55 mH, C_{dcst}=1600 µF (FFLC6L1607K by AVX Corp.), V_{dcst}=750 V, V_{igbt}=750 V, I_{igbt}=60 A, IGBT: FF100R12YT3 by Infineon Inc. Passive filter: 445 kVar, C_f=8780 µF (2GCA280774A0030 and 2GCA280780A0030 by ABB), L_f=9.54 µH, Q=30	Source: 3-ph, 400 V, 50 Hz, L_s=20 µH Transformer: 1000 kVA, ddy11, V_{pri}=400 V, V_{sec}=235.5 V, L_l=6 % Rectifier: C_{dc} =1000 µF (FFVE6K0107K by AVX Corp., 10 in parallel), I_{Dave}=560 A, diode: DD600N12KOF by Infineon Inc. (2 in parallel) Chopper: 3-phase, f_s=1 kHz, L_{dc}=96 µH, C_{dc}=2100 µF (FFLI6B2407K by AVX Corp.), V_{igbt}=300 V, I_{igbt}=1120 A, IGBT: FD600R06ME3 by Infineon Inc. (4 in parallel) Passive filter: 70 kVar, C_f=1392 µF (MKK400-D-20-01 B25667C3397A375 and B25669A3996J375 by Epcos), L_f=60 µH, Q=30

2.1. 12-Pulse Thyristor Rectifier with Hybrid Filter (TRHF)

Fig. 2 shows the system configuration of the 12-pulse thyristor rectifier with hybrid filter. The design of the system is carried out to fulfill the requirements provided in Table I. 12-pulse rectifier configuration is chosen as it provides significantly less input current THD as compared to a 6-pulse rectifier and is less complicated as compared to a 24-pulse rectifier. System simulations are carried out with the load curve given in Fig. 1 and variation of the required reactive power compensation is figured out to keep the power factor (PF) greater than 0.98. The average reactive power compensation is provided by the fixed 11th harmonic passive filter and DSTATCOM is used to compensate for the variable reactive power demand. This leads to the rating reduction of the VSC working as DSTATCOM. At the output of the rectifier an L-C filter is used to keep the output voltage ripple < 2%. Value of inductance is kept low to achieve low input current THD [6]. This leads to relatively bigger capacitive filter. The detailed design procedure is explained in [6]. Table II provides various system parameters of TRHF system. Selection of semiconductor is carried out depending on the next safe voltage rating commercially available and current margin is maintained at ~100%. Commercially available capacitors are used with closest safe voltage and rms current ratings. Magnetic components are designed using the standard design procedures [9].

2.2. 12-Pulse Diode Rectifier followed by Chopper (CRPF)

Fig. 3 shows the system configuration. The design of the system is carried out to fulfill the requirements provided in Table I [10]. Because of front end 12-pulse rectifier configuration the displacement power factor (DPF) of the system ideally remains to be unity. However due to the leakage inductance and transformer magnetizing current DPF is below unity (approximately 0.96-0.97). Moreover, due to the distortion factor, the power factor of the system

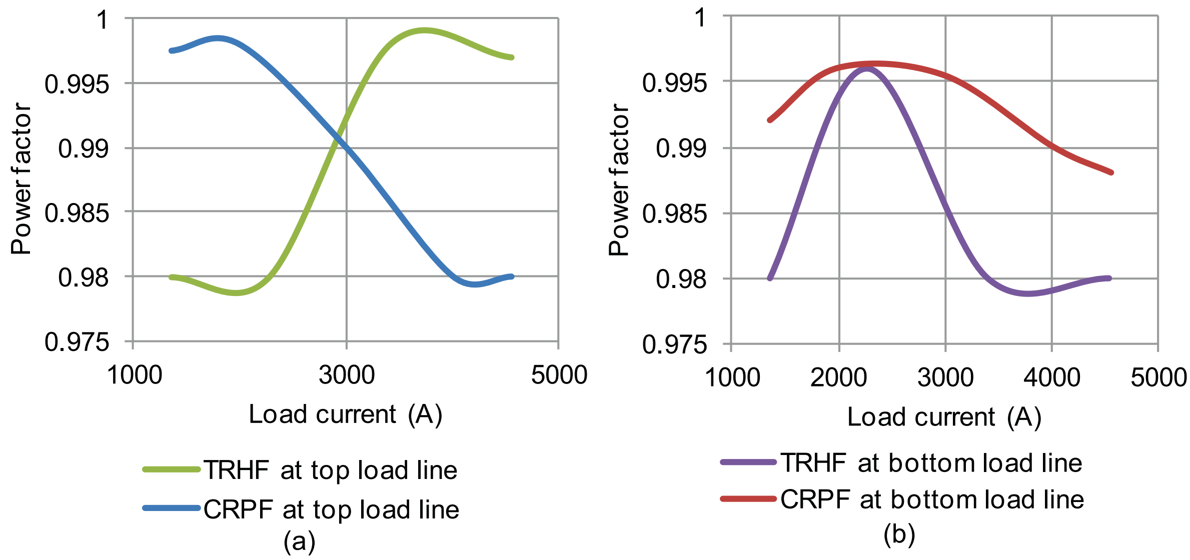


Fig. 4 (a) and (b). Variation of input power factor of TRHF and CRPF at top and bottom load lines.

reduces further at light load conditions. To deal with this problem, an 11th harmonic filter is added to reduce the current THD and improve the power factor by supplying a small amount of reactive power. To improve the harmonic cancellation properties of passive filter a relatively bigger input inductor is added at input. In order to control the output current a 3-phase chopper is utilized. It is applied in interleaving mode for reducing the output filter size. Inductor is designed for 5% current ripple. The chopper capacitor filter design is carried out to fulfill output voltage ripple requirement. The capacitance value comes out to be considerably lower as compared to TRHF because of bigger dc inductors and higher frequency of operation. The switching frequency is kept low (1 kHz) to reduce switching losses. A capacitor is added at the input of chopper section to reduce the effect of the current ripple on up-stream circuit components. Table II provides various system parameters of the rectifier system. Selection of semiconductors and other components is carried out employing the same criteria as explained in the previous section.

3. Comparison

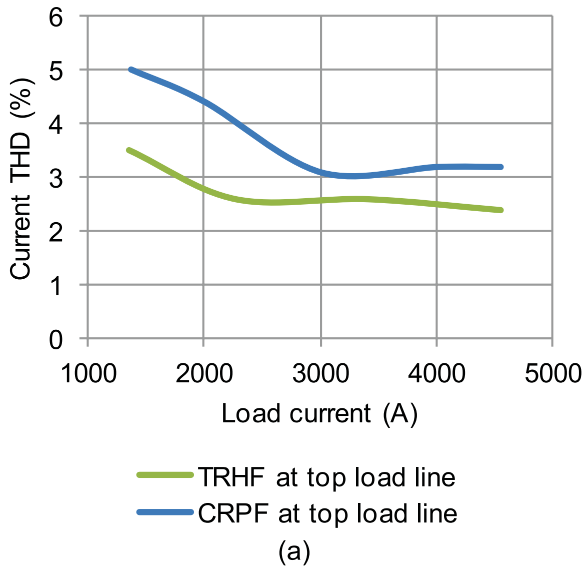
Comparison of the two systems is carried out for supplying power to the load specified by eq. (1) and (2) and meeting the specification provided in Table I. The comparison is carried out in term of performance (input power factor and current THD), efficiency, size and cost.

3.1. Power Quality

Fig. 4 (a) and (b) show the variation of power factor (PF) of the two topologies along the top and bottom load lines. It can be observed that with the help of appropriate reactive power compensation both systems are able to meet the requirement i.e. PF≥0.98. Variation of input current THD is depicted in Fig. 5 (a) and (b). It can be seen that due to bigger passive filter TRHF provides better harmonic cancellation characteristics. Also, with CRPF at light load, current THD becomes marginally higher than 5% limit.

3.2. Efficiency

Fig. 6 (a) and (b) show the comparison of estimated system level efficiencies which includes effect of losses from semiconductors and magnetic components. Semiconductor losses are estimated using parameters from datasheets and MATLAB and PLECS simulation models. PLECS utilizes forward characteristics to compute the instantaneous conduction losses, which are averaged over the cycle to compute the average conduction loss. For switching



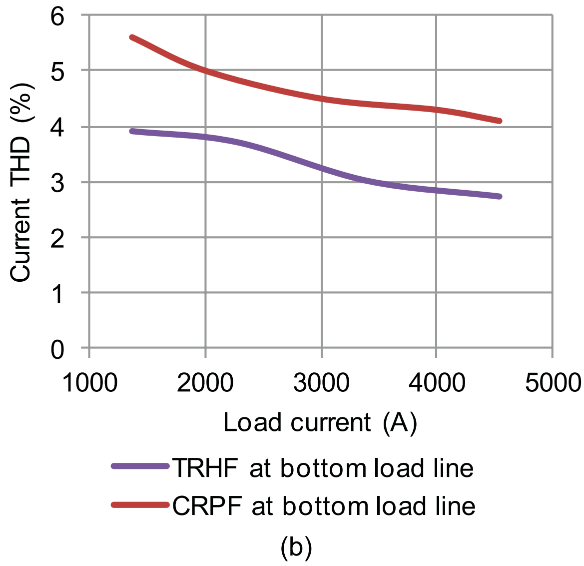


Fig. 5 (a) and (b). Variation of current THD of TRHF and CRPF at top and bottom load lines.

loss computation, the energies involved at turn on and off instances with respect to device current and voltage (as provided in the data sheet) are added over a period of unit time. The input data corresponds to the maximum junction temperature; therefore the estimated semiconductor losses are pessimistic. Magnetic losses are determined using standard design equations. For low-voltage high-current applications CRPF appears to be the clear winner. However, at top load line under full load condition, efficiencies of two systems are fairly close. In order to investigate the reasons behind the lower efficiency of the TRHF, one needs to look at the contribution of different system components to the power losses. Fig. 7 shows the distribution of losses. The largest contributors to the losses are thyristor conduction losses and transformer losses. For high-current low-voltage applications, the choice of thyristor vs. diode makes a significant difference. Thyristor conduction losses are significantly higher than the diode conduction losses because of two reasons: (1) thyristor has higher on state voltage drop for the same current and voltage rating and (2) lower current flows through the diode bridge rectifier in case of CRPF due to higher intermediate DC link voltage. However, losses in chopper section offset this advantage. As depicted in Fig. 7 at full load along top load line, combined losses (11.9 kW) of diode rectifier and chopper section overweigh losses (9.4 kW) in the thyristor rectifier. As the voltage demand drops further chopper plus diode rectifier losses become fairly comparable at full current along bottom load line. However, there are losses in the other components, mainly transformer and input filter that play significant role in determining the overall efficiency.

As far as transformer losses are concerned, it can be optimized for particular topology and application. However, to make a fair comparison, here transformer material (CRGO M6, 0.3 mm lamination thickness), flux density (1.5 T) and current density (4 A/mm^2) are kept constant. This leads to slightly higher full load efficiency (neglecting losses due to harmonics) in case of the chopper-rectifier transformer at almost the same transformer size (98.55 % for TRHF and 98.75 % for CRPF). If one wants to make transformer efficiencies equal for both rectifier systems, the difference between system efficiencies of the CRPF and TRHF can be reduced. Moreover, around rated current at top load line, efficiency of TRHF becomes marginally higher than CRPF. Large current rectifier transformers have higher copper losses and merely 10-15% iron losses. This explains the behavior of efficiency curves shown in Fig. 6 with peak system efficiency occurring at relatively lighter loads. Other dominant contributors to the losses of TRHF are the AC passive filter and the DSTATCOM. Bigger AC passive filter employed with TRHF (445 kvar) as compared to CRPF (70 kvar) leads to higher losses for TRHF. Due to DSTATCOM action there is a significant dip in the system efficiency of TRHF

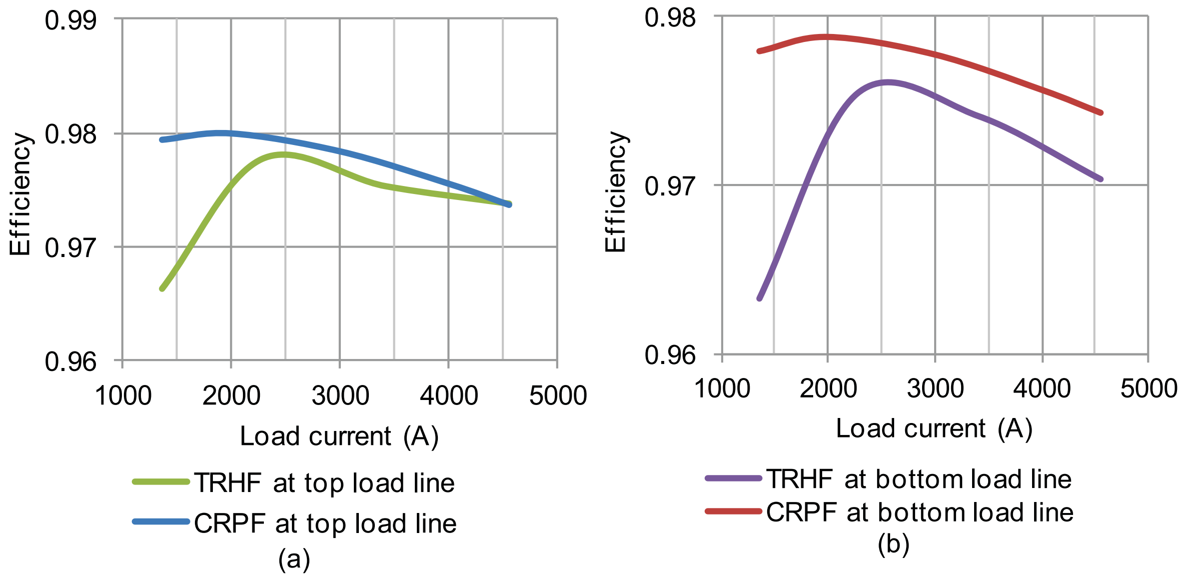


Fig. 6 (a) and (b). Variation of estimated efficiencies of TRHF and CRPF at top and bottom load lines.

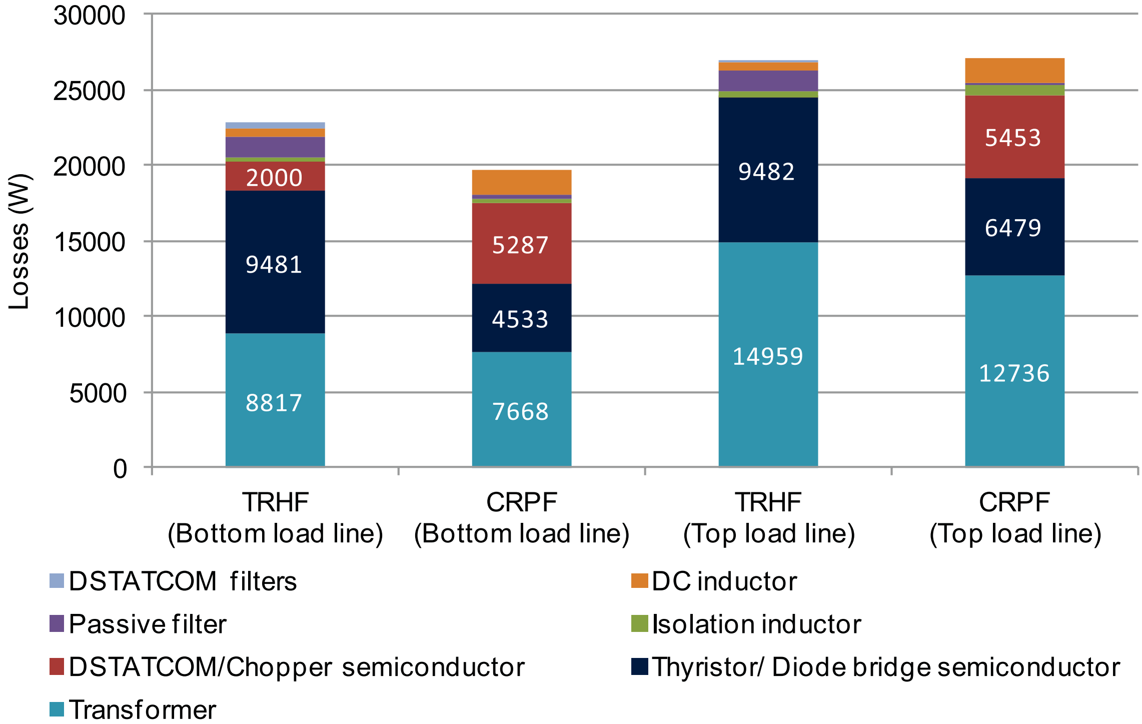


Fig. 7. Distribution of estimated losses of different components used for TRHF and CRPF.

at light load condition. Difference in efficiencies of CRPF and TRHF increases along the bottom load line due to (1) loss in thyristor rectifier becomes comparable to combined losses in diode rectifier and chopper section (diode rectifier loss reduces due to reduced current flow as load power reduces, however, thyristor rectifier see the same current, chopper losses remain almost the same) and (2) requirement of continuous DSTACOM action, especially around rated and low load current.

As discussed, in the case of CRPF, semiconductor losses occurring in chopper section leads to significant amount of losses apart from transformer and diode rectifier losses. Semiconductor losses in chopper section mainly consist of conduction losses (>90%). This is achieved by keeping switching frequency of the chopper section low (1 kHz). Losses in the output inductor are also significant at 6.2% and 8.5% for rated load current operations at top and bottom load lines respectively.

3.3. Size

Fig. 8 shows the comparison of the estimated volumes of the two considered rectifier systems. Volumes of the selected components are calculated with the help of dimensions provided in datasheets. The transformer and filter inductors are the main contributors to the size of the system. As discussed in the previous section, the sizes of the transformers are nearly similar for both topologies. However, sizes of AC and DC inductors are bigger for CRPF. DC inductor size can be reduced by increasing the no of phases or switching frequency of chopper section, however, increase in switching frequency will lead to higher switching losses. AC inductor size comes out to be bigger for CRPF because of lower capacitive reactive rating of passive filter. But this difference in inductor sizes is offset by AC capacitor used for passive filter of TRHF. This leads to overall bigger size of TRHF as compared to CRPF.

3.4. Cost

Major part of the cost of the system comes from magnetic components especially the transformer. Since the TRHF transformer is slightly bigger than CRPF transformer, cost of the former will be marginally higher. To compare the cost of the filter inductors, peak energy rating can be compared (at the same operating frequency). Line frequency inductor peak energy ratings are 173.6 J and 126.8 J for TRHF and CRPF respectively, whereas DC side inductors ratings for TRHF and CRPF are 140.5 J and 399.9 J respectively. Another way to estimate the cost is to compare the iron and copper weight. Estimated iron and copper weight of various inductors used for TRHF are 205 kg and 122 kg respectively. For CRPF inductor iron and copper weight stands at 426 kg and 203.5 kg respectively. Therefore the material cost of

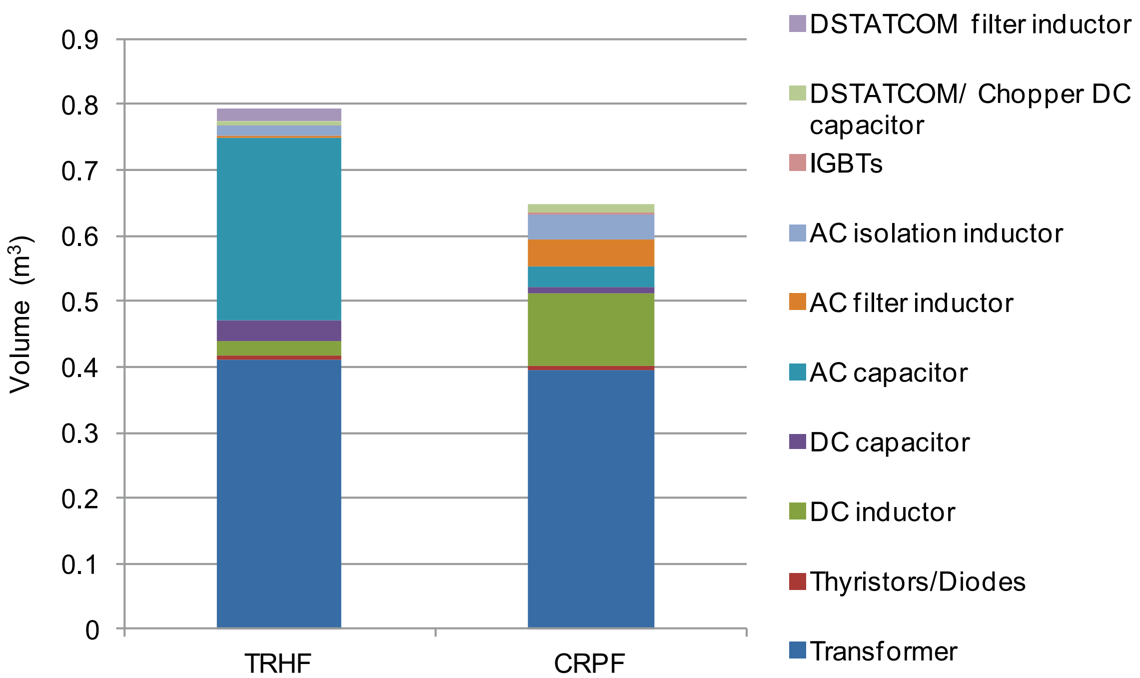


Fig. 8. Estimated size of different components used for TRHF and CRPF.

Table III: Total ratings of semiconductor components

Semiconductor components	Installed Rating (MVA)	
	TRHF	CRPF
Thyristors or Diodes	23.04	17.28
IGBTs and Diodes	1.44	8.64

inductors will be almost double in case of CRPF as compared to TRHF. For comparison of semiconductor costs one need to estimate VA ratings of the components. Table III provides installed VA ratings of different components. However actual market price of semiconductor switches depend on many factors apart from VA rating, such as, production volume, demand and availability etc. Because of these reasons normally dual IGBT leg is priced less as compared to the chopper leg of the same rating. Thyristor modules are priced higher than diode modules of similar rating. Apart from these, cost of DC and AC capacitors is the remaining major part. Since both AC and DC capacitor ratings are higher in case of TRHF, cost of the same will also be higher. Protection equipments (circuit breakers, fuses and relays etc.), control and signal processing systems and mechanical housing also contribute significantly to the cost of the overall system. However, cost assessment of these components is out of the scope of this work.

4. Conclusions

Two topologies of high-current rectifiers, thyristor rectifiers with hybrid filter and chopper-rectifier with passive filter have been compared for feeding a high-power (1 MW) high-current (4.5 kA) load with a set of specifications. The two systems have been designed to meet certain power factor, input current THD and output voltage and current ripple requirements. The analysis shows that CRPF provides better efficiency as compared to TRHF. This is caused by dominant thyristor conduction losses for low-voltage, high-current application as compared to losses in the diode-rectifier and chopper section. Hybrid filter losses also contribute to lower efficiency of the TRHF especially when DSTATCOM starts operating to improve power factor. However, this depends on the type of load. For loads with relatively lower-current at higher operating voltages and lighter filter requirements, TRHF can provide better efficiency. Moreover hybrid filter can be a good power quality improvement option for retrofit applications. The size of the TRHF is higher than the CRPF due to the bigger input passive filter. Costs of the two systems have also been compared. Two circuits found to have almost same transformer cost, however, TRHF incurs higher cost of AC and DC capacitors. Magnetic cost component is expected to be higher for CRPF.

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