A Comparison Study of High Power IGBT-Based and Thyristor-Based AC to DC Converters in Medium Power DC Arc Furnace Plants

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***Abstract*—With the advent of semiconductors manufacturing technology, current and voltage ratings of Insulated Gate Bipolar Transistor (IGBT) modules have been increased. Because of the faster switching capability, thyristors are being supplanted by the IGBTs. This new generation of IGBT modules are being increasingly used in applications such as AC/DC choppers to produce large controlled currents. Typical DC arc furnace plants use thyristor-based AC/DC converter in their rectifying system. However, implementation of the IGBT-based rectifiers offer many advantages compared with the conventional thyristor-based rectifiers. In this paper a comprehensive comparison between these two types of rectification systems has been performed. A medium power DC arc furnace plant of 800V, 100 kA and 80 MW is simulated in MATLAB/SIMULINK and through the simulation results, IGBT-based and thyristor-based rectification systems are compared to one another.**

Keywords— DC arc furnace; Harmonic; IGBT-based rectifier; Power quality; Thyristor-based rectifier.

I. INTRODUCTION

DC arc furnace plants offer many advantages compared with the AC arc furnaces. The main advantage is the capability of the output voltage regulation due to the AC/DC controllable converter. As a result, the furnace current can be controlled as well and this leads to less power quality issues. The thyristor-based rectifiers are by far the most widely used technology in DC arc furnace plants. However, they have several drawbacks such as input current harmonics and low operating power factors [1-3]. Fig. 1 shows the input current of the rectifier transformer in the DC arc furnace plant with the thyristor-based AC/DC converter which strongly suffers from the low order harmonics. According to the different standards such as IEEE, IEC, VDE, etc. [4], the power electronics equipment are only allowed to inject a limited amount of the current harmonics into the power grid. Hence, the thyristor-based rectifiers require additional equipment such as input harmonic filters, Static Var Compensators (SVC), etc., which increases the costs as well as complexity. Moreover, the losses associated with this equipment are considerable. With the advent of the Insulated Gate Bipolar Transistor (IGBT) modules and their manufacturing technology, ratings of these switches have been increased. Therefore, the thyristor-based rectifiers are being gradually replaced with the IGBT-based rectifiers [1, 3]. The IGBT-based rectifier produces less input harmonics and also works at higher power factors and eliminates the need for additional costly equipment [5]. In addition, owing to the higher switching frequency available, the IGBT-based rectifier has a faster dynamic response. Moreover, increasing the switching frequency helps to avoid those frequency bands in which the noise is disruptive. This paper compares the aforementioned two rectification systems in medium power DC arc furnace plants in terms of total harmonic distortion (THD), power factor (PF), arc stability, etc.

In the rest of the paper, section II compares the conventional thyristor-based rectifiers to recently developed IGBT-based rectifiers. Section III discusses about the design criteria of the IGBT modules. Section IV presents the model and the circuit parameters of the simulated DC arc furnace plant. Section V analyses the simulation results to evaluate the performance of the two rectification systems. Finally, in section VI the main results are concluded.

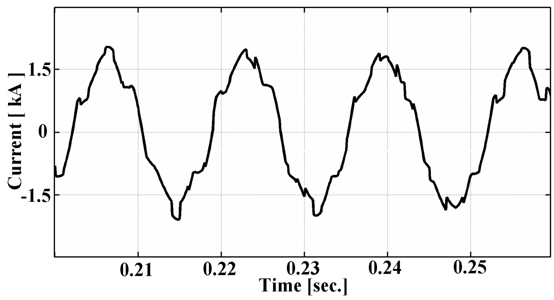


Fig. 1. Current distortion in primary side of the rectifier transformer (at PCC) using thyristor-based technology without compensation (phase-a).

II. COMPARISION OF The IGBT-BASED AND THYRISTOR-BASED CHOPPERS

A conventional 12-pulse thyristor-based AC/DC converter is shown in Fig. 2. It is composed of two paralleled 6-pulse converters which are fed through Δ-Y and Y-Y transformers. The forgoing configuration is used to obtain 30° phase shift between the two secondary windings required for achieving the 12-pulse converter. Fire angles of the thyristors are usually

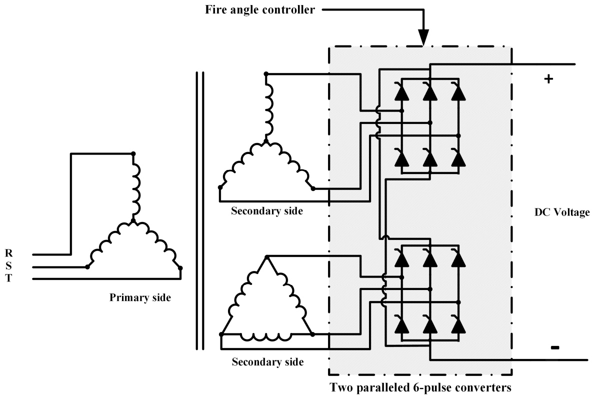


Fig. 2. 12-pulse thyristor-based AC/DC conversion system

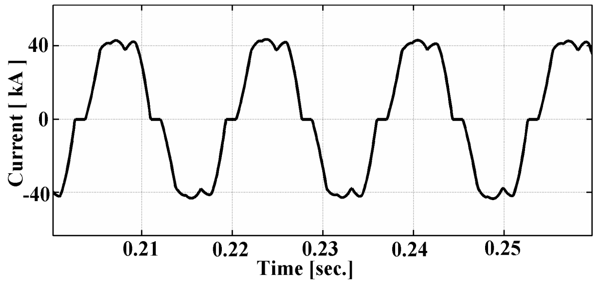


Fig. 3. Input current waveform of the thyristor-based AC/DC converter without compensation (phase-a).

controlled with a PI feedback controller. The input current waveform of the converter is shown in Fig. 3.

Investigating the converter input current harmonic spectrum shows that it mainly contains harmonics of order 12k±1. It also produces reactive power which lowers the input power factor. Therefore, it is essential to add harmonic filters and reactive power compensators to reduce these harmonics, which imposes additional costs. Moreover, it causes high current ripple and high voltage fluctuations at the load side in case of the DC arc furnaces. Despite the above-mentioned problems for the thyristor-based rectifiers, they are very reliable as well as high efficiency.

The other rectification system that is increasingly being used in the industry processes is the IGBT-based AC/DC converter. The most common configuration of the forgoing converter used in the medium power DC arc furnace plants is the 12-pulse transformer/rectifier with single chopper load which is shown in Fig. 4. The other configurations can be found in [3]. The 12-pulse IGBT-based rectifier contains two paralleled chopper cells to produce a large current at the load side. Generally, the minimum required phase shift in the transformer secondary windings depends on the number of chopper cells and can be calculated as below:

$$\theta = \frac{60}{number\, of\;\; chopper\, cells} \tag{1}$$

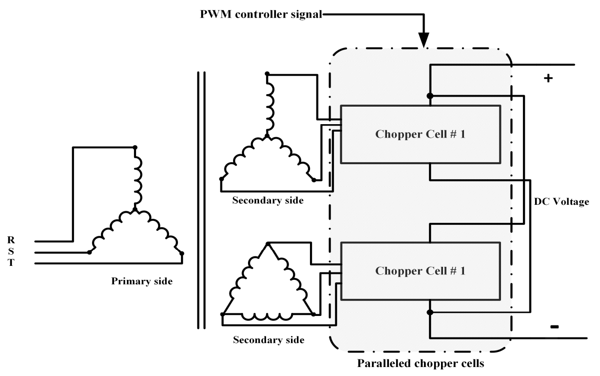
As it is shown in Fig. 4, two chopper cells are paralleled and each one is composed of the input capacitive filters, a full bridge unregulated diode rectifier, chopper input capacitor and an IGBT DC/DC chopper. Depending on the load voltage, the IGBT-based DC/DC chopper can be designed in the form of a step-up or step-down converter but in the case of DC arc furnaces a step-down (buck) chopper is usually used. A step-down transformer supplies the unregulated diode rectifier. The DC/DC chopper is fed from the bulk DC produced by the unregulated diode rectifier. It must be noticed that whenever the bulk DC bus energizes, an inrush current passes through the IGBT modules which may damage the switches [6]. Therefore, it is of great importance to pre-charge the input filters. The IGBT switches are usually pulse wide modulated (PWM) to provide the desired voltage for the load. Working principle of the chopper cell is very simple. When the IGBT switch is on, current flows to the load through the switch. After the IGBT turned off, the freewheeling diode starts to conduct and the load current passes through it. Since the arc furnace is an inductive load, the current flow is continuous. The gate-turn-off capability of the IGBT modules enables the switches to commutate several times a period and lets the current or voltage to be pulse-wide modulated. Since it uses a full bridge diode rectifier (α=0), it produces less harmonics and minimizes voltage notching compared with the thyristor based chopper ($\alpha \neq 0$).

Fig. 5 shows the simulated input current of the IGBT-based AC/DC converter. The power factor is high and almost constant and can be controlled as well. Furthermore, increasing the switching frequency reduces the load current ripple and improves the power quality. However, the higher the switching frequency, the higher the switching power losses. Consequently, a tradeoff is required between the power quality enhancement and the switching losses reduction. Although, the IGBT-based rectifiers have an additional power conversion stage compared with the thyristor-based rectifiers and they seem to have more power loss but, in section 5, it is shown that the overall system efficiency (including the rectifier transformer, switching losses, filters, etc.) in case of the IGBT-based rectifier is higher than that of the thyristor-based rectifier. Other advantages of the IGBT-based rectifier are listed below:

- Because of the faster switching capability of the IGBT switches, it has a better dynamic response compared with the thyristor-based rectifier.
- The control system is simpler than that of the thyristor-based rectifier.
- In the component failure events, since it uses n-1 redundancy the system is continually available.
- Since the DC/DC IGBT chopper can be either a buck or boost converter and can exactly regulate the output voltage and current, the need for auto-transformers and on-load tap changers is eliminated which reduces initial and maintenance costs.

III. HIGH POWER IGBT MODULES

In high power applications such as medium voltage DC arc furnace plants, HVDCs, etc. it is necessary to have power switches in which the voltage and current ratings are over thousands volts and amperes. In these applications, multiple



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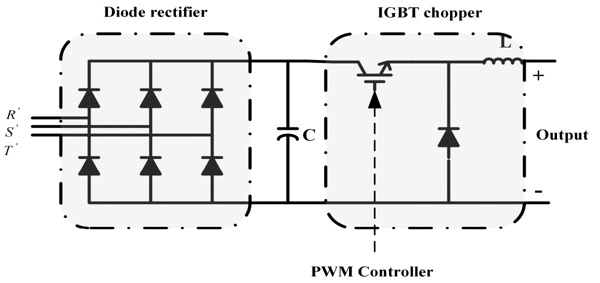


(b)

Fig. 4. The IGBT-based AC/DC rectifier. (a) General structure of the 12-pulse IGBT-based AC/DC rectifier. (b) Circuit configuration of the chopper cell.

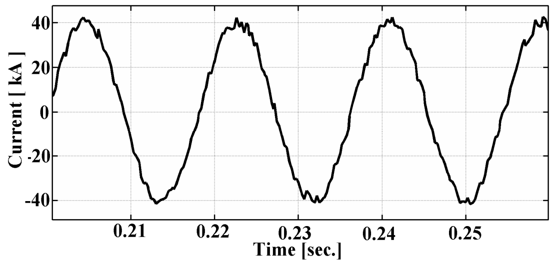


Fig. 5. Input current of the IGBT-based AC/DC converter (phase-a).

cells are paralleled to achieve the required current rating [7]. Similarly, in order to increase the voltage rating, a number of cells are cascaded in series. Nominal voltage of the IGBTs recently revealed in the market is up to 6500 volts therefore, there is no concern with the voltage rating of the IGBTs in the medium power arc furnace applications. For the purpose of reliable and stable operation of the paralleled cells, many considerations must be taken into account. For balanced and equal current sharing between the switches, the IGBTs must switch on and off at the same instant. In theory, to achieve this objective, the IGBTs must have the same characteristics which is not possible practically. Therefore, Auxiliary circuits are utilized to mitigate the effect of dissimilarity. Here, the most important factor that meanly affects the module operation is the temperature rise in the semiconductor switches. In such these cases, there must be enough information that how the characteristics of the IGBTs change as the temperature increases. The switches must be properly water-cooled as well. Suitable feeding of the gates, equal current division, on-state Losses balance and thermal stability are some of the essential designing considerations of the IGBT modules. The detailed information of designing the IGBT modules is presented in [7].

Although parallel operation of IGBT cells require a more complex interconnection, but using these modules offer many benefits. The cooling process and cooling system are more efficient. Also, power loss in case of using multiple paralleled cells is considerably less than the power loss in a single switch with the same rated voltage and current. Likewise, the efficiency and reliability of the system can be increased using Built-In Redundancy (BIR).

IV. TARGET DC ARC FURNACE DESCRIPTION

A. Circuit parameters

A DC arc furnace plant of 800V/100kA/80MW is simulated by MATLAB/SIMULNIK. A PI feedback controller is designed to control the firing angle (α) of the 12-pulse thyristor rectifier bridge. In case of the IGBT-based rectifier, the switches are pulse wide modulated through the PI controller. Circuit parameters are tabulated in Table. I.

TABLE I. OPERATING CONDITIONS AND CIRCUIT PARAMETERS

Circuit Parameter	Value
Input voltage	22 kV
Input current	1800 A
Frequency	50 Hz
Nominal arc voltage	800 V
Output chock inductance	200 µH
Firing angle	30~50°
Duty ratio of PWM	40-80 %
P_0	1.37×10^5 W
τ_c	3×10^{-6} s
Switching frequency	1 kHz

B. DC Arc Furnace Model

Cassie and Mayr black-box arc Models are commonly used to describe the arc behavior. Both of these models treat the arc resistance as a dynamic variable. Whereas Mayr model is proper for characterizing the low current arcs, Cassie model better describes the high current arcs. In this paper Cassie electric arc model is used for modelling the electric arc, which is presented as a first-order differential equation as below:

$$\frac{1}{G_c}\frac{dG_c}{dt} = \frac{1}{\tau_c}\left(\frac{u\times i}{P_0} - 1\right) \tag{2}$$

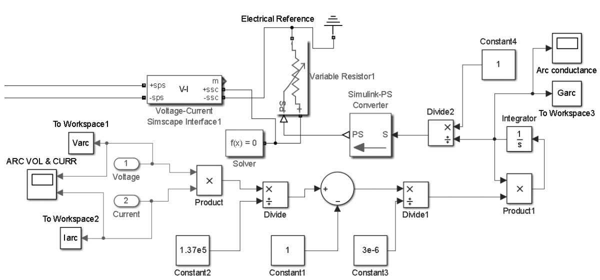


Fig. 6. The block diagram of the Cassie arc model implemented in MATLAB/SIMULINK

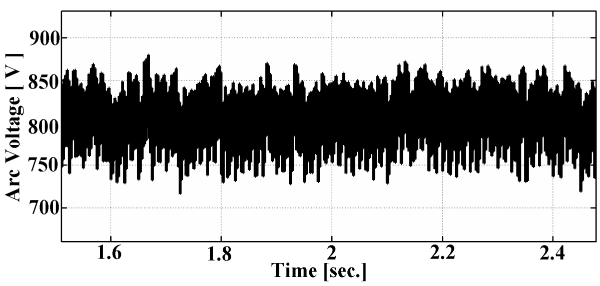
where G_c is the arc conductance, τ_c is the time constant of the arc, P_0 is the power loss of the arc, i is the current passing through the electric arc channel and u is the arc voltage. Block diagram of the model is shown in Fig. 6

V. SIMULATION RESULTS

In order to analyze the performance of the aforementioned two rectification systems in DC arc furnace plants, a medium power DC arc furnace of 80MW is simulated via MATLAB/SIMULINK. The parameters of the circuit and operating conditions are listed in Table. 1. Each rectification system is simulated separately with the same operating conditions. The recorded data are compared from different point of views as follows:

5.1. Arc Stability

Arc instability lowers the productivity of the DC arc furnace plant. Arc voltage fluctuations may cause the arc instability. Actually, the voltage fluctuation is an index of the arc instability and the higher the voltage fluctuations, the higher the arc instability [8, 9, 11]. Likewise, fluctuations of the arc voltage can bring about flicker. Investigating Fig. 7, it can be obviously seen that the arc voltage fluctuations in the IGBT-based rectifier is less than that of the thyristor-based rectifier and hence the arc stability is improved.



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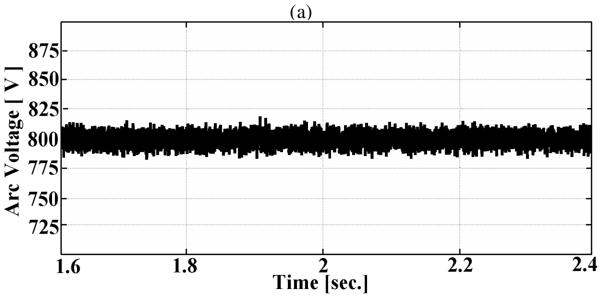


(b)

Fig 7. Simulation arc voltage waveforms in the DC arc furnace using the thyristor-based and the IGBT-based AC/DC converters. (a) Arc voltage waveform using the12-pulse thyristor-based rectifier. (b) Arc voltage waveform using the 12-pulse IGBT-based rectifier.

Whereas the voltage waveform variations is about 100 Volts in Fig. 7(a), it only varies in a small range of 20 Volts in Fig. 7(b). In the same conditions, the average arc voltage is also increased due to reduction of the source voltage short circuit time period which is caused by the gate-turn-off ability of IGBTs.

5.2. Current Quality

5.2.1. Input Current Harmonics

It is known that the phase-controlled rectifiers inject harmonics to the power system which the facility is being fed from. These harmonics cause the input current to be distorted. Fig. 1 shows the distortion in the rectifier transformer primary side current in the simulated DC arc furnace. Also, these types of high power rectifiers provide a poor power factor. The power factor in the proposed case study is 0.729. Consequently, for the purpose of the harmonic reduction and the power factor compensation, additional equipment such as active or passive filters and SVCs must be necessarily installed. This equipment occupies more space and they increase the costs as well as the power losses.

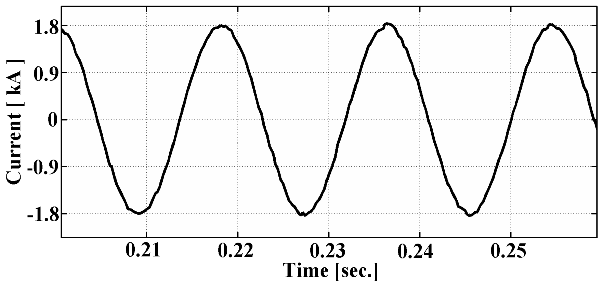


Fig. 8. Input current waveform (at PCC) in DC arc furnace plant using the 12-pulse IGBT-based chopper without compensation (phase-a)

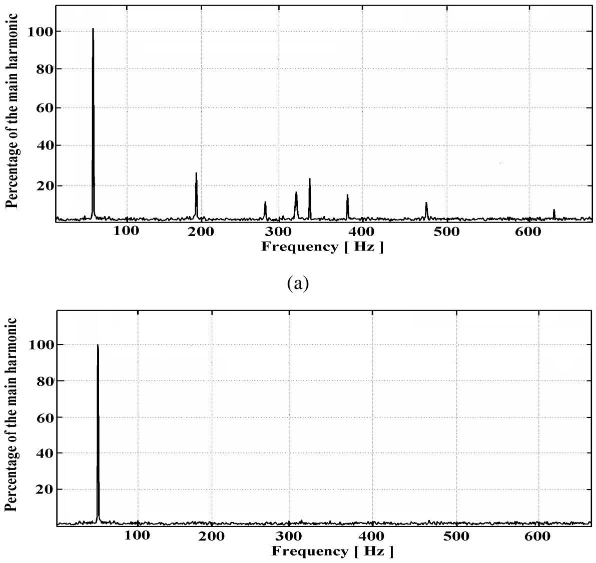
On the other hand, as can be seen from Fig. 8, input current waveform in case of the IGBT-based AC/DC converter is almost sinusoidal at the same conditions. Likewise, the power factor is 0.945 and it is almost constant and does not need to be compensated. In order to analyze the power quality in details, the harmonic spectrums of the input currents are plotted in Fig. 9. Analyzing the FFT of the input currents shows that the harmonics in case of the IGBT-based AC/DC converter are much fewer than that of the thyristor-based rectifier. Total Harmonic Distortion (THD) which is an index of power quality can be expressed via the following formula:

$$THD = \sqrt{(\frac{I_s}{I_{s1}})^2 - 1} \tag{3}$$

Whereas input current THD is 3.1% in case of using the IGBT-based rectifier, it is 34.2% in case of the thyristor-based rectifier. Existence of the DC term in the primary side current in the case of thyristor-based rectifier can also bring about severe problems for the power system grid.

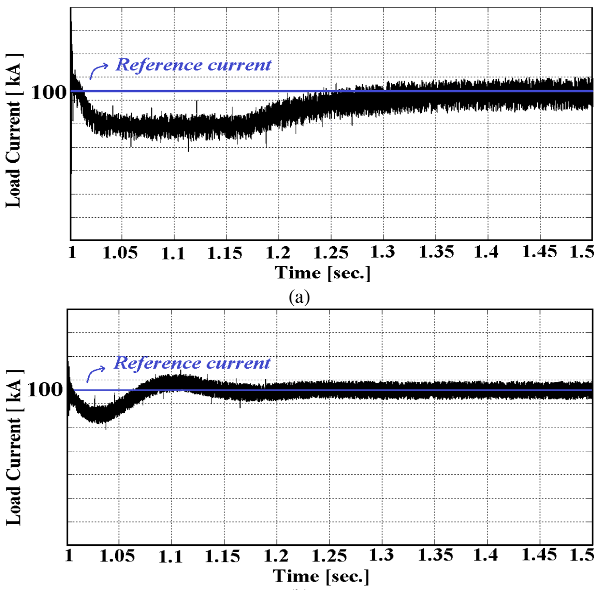
5.2.2. Output Current Ripple

The thyristor-based AC/DC converter produces a large load current ripple which is related to the low switching frequency of the thyristors. On the other hand, simulation results show that using the IGBT-based rectifier leads to the low load ripples. The reduction of the load ripples is caused by increasing the switching frequency which is available for the IGBT switches. The simulated load current is shown in Fig. 10.



(b)

Fig. 9: FFT of the input current (phase-a) of the rectifier transformer using two mentioned rectification systems in the DC arc furnace plant (without compensation). (a) FFT of the input current of the rectifier transformer using the thyristor-based rectifier. (b) FFT of the input current of the rectifier transformer using the IGBT-based rectifier.



(b)

Fig. 10. Load current variations during the stepwise disturbance. (a) Load current of the arc furnace using the thyristor-based AC/DC converter. (b) Load current of the arc furnace using the IGBT-based AC/DC converter system.

5.3. System Power Loss

The power losses in different sections of the simulated DC arc furnace plant are categorized and plotted in Fig. 11 [10]. The following bar graph shows that a great part of the losses are related to the rectifier transformer. The rectifier transformer of the IGBT-based rectification system has less power loss than that of the thyristor-based rectifier. Actually, the rectifier transformer needs a reduced VA while using the IGBT-based rectifier. Maximum Current and voltage of the load do not happen in the same instant. However, the thyristor-based rectifier is always designed based on the maximum voltage and current rating, which will necessitate the use of a high VA rectifier transformer and transformer overdesign. On the other hand, when using the IGBT-based rectification system, components are usually designed based on the maximum power that load requires. This helps the system components to be smaller is VA, lighter in weight, more energy efficient and also more cost effective. Moreover, since the IGBT-based rectifier produces less harmonics, the eddy current and conduction losses of the rectifier transformer is decreased.

IGBTs switching losses, on-state losses and snubber losses are included in IGBT chopper loss bar. As seen in previous section, since the IGBT-based rectification system doesn't bring about serious power quality issues, the line filter losses are eliminated. The simulation results show that the overall rectification system loss of the IGBT-based system is higher than the thyristor-based system due to the switching losses of IGBTs at 1 kHz. However, the overall system loss is decreased due to the elimination of the line filter and reduced transformer losses. In accordance to the total system loss shown in Fig. 11, the system efficiency can be calculated to be 92.3 % for the thyristor-based system and 95.2% for the second system at the same conditions.

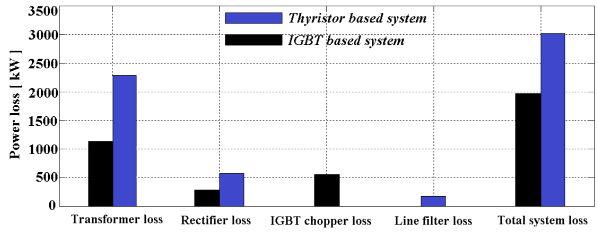


Fig. 11. Bar graph of the power losses in different parts of the system, considering both the thyristor-based and the IGBT-based AC/DC converter.

5.4. Control Systems and System Response Dynamics

For evaluation of the system response dynamics, a disturbance is imposed to the system and the load current variations are plotted in Fig. 10. The disturbance is applied through a sudden stepwise reduction of the arc voltage. In the thyristor-based rectification system, the control system which is synchronized with the line voltages sends 12 pulses that are 30 degree out of phase. These pulses can turn on the thyristors in a specified pattern. Although the thyristors can be turned on in this way, but they must wait for the AC line to turn them off. This inherent delay increases the system response time. On the other hand, IGBTs can be either turned on or turned off by the gate signals lowering the system response time to load variations. Fig. 10 shows that the system response is faster in the IGBT-based rectification system compared to the thyistor-based system.The qualitative comparison including the cost and reliability issues are summarized and presented in Table. II.

TABLE II. QUALITATIVE COMPARISON OF THE TWO DISCUSSED RECTIFICATIONS SYSTEMS

Rectification System	**Thyristor-based AC-DC Converter**	**IGBT-based AC-DC Converter**
Cost	**Reasonable** (for both low-power and high-power applications)	**High** (for high-power applications) **Reasonable** (for medium and low-power applications)
System Performance	**Advantages:** 1. Both the installation and maintenance costs are reasonable. 2. Its reliability is proven through working under severe operational conditions over many years. 3. It needs a reduced number of paralleled modules in accordance to the thyristor ratings available in the market. 4. The system fault diagnostics is easy. **Drawbacks:** 1. High arc voltage fluctuations makes the electric arc more unstable. 2. It injects a great amount of harmonics to the power grid and static Var compensators and input filters are required. 3. System response time is slow. 4. The output current ripple is high. 5. The operating system power factor is low.	**Advantages:** 1. Arc voltage fluctuations are reduced. 2. It causes less power quality problems and the need for reactive power compensators are eliminated. 3. Provides high operating power factors, eliminating the need for any compensation. 4. System response time to disturbances is reduced. 5. At the same conditions, the system efficiency is higher than the thyristor-based. (without any compensation) 6. The rectifier transformer can be designed smaller in size and VA. 7. The need to on-load tap changers and auto-transformers is eliminated. **Drawbacks:** 1. It requires an increased number of IGBT modules which lowers the reliability. 2. The system fault diagnostics is time consuming and costly. 3. The designing and instructing process imposes additional investments. 4. It is recently developed and many facilities still prefer the conventional system.

VI. CONCLUSION

This paper performs a comprehensive comparison between the IGBT-based and the thyristor-based rectification systems in terms of response dynamics, arc stability, power quality, etc. Whereas the IGBT-based rectifiers work at high switching frequencies and use Pulse Wide Modulation (PWM) to regulate the output current, the thyristor-based rectifiers work at low frequencies and use the phase shifting method. The simulation results prove that implementing of the IGBT-based rectification system in a DC arc furnace causes less power quality problems compare with the thyristor-based systems. Although the IGBT switches cause additional switching losses, but the results show that the overall system losses is reduced. Nevertheless, the thyristor-based rectifiers are more reliable. Likewise, costs of the thyristor-based rectification systems are lower and from both foundation-cost and life-cycle-cost viewpoints they are more favorable.

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