Use of three-phase rectifiers in ESP's for low resistivity applications

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1. Abstract

This paper describes the use of three-phase HV transformer-rectifiers in low resistivity applications, as an alternative to switch mode power supplies (SMPS). The operation of these HV power supplies will be described showing the most important waveforms. Then the information that should be included in the rating plate for performing theoretical calculations will be reviewed. Afterwards the results obtained in a practical application will be presented. Finally some technical considerations regarding the firing of the thyristor controller will be given.

2. Introduction

In the abatement of low resistivity particulate is well known that the use of a voltage waveform with low ripple is advantageous, as it gives a higher corona power and therefore a lower dust emission. This feature has been better illustrated after the introduction of the SMPS-units in the recent years. In spite of the advantages of these HV units, some disadvantages still exist, like output power limitation, high price, complexity and reliability.

Because three-phase TR's have a simple and rugged construction, in practice they don't limitations have regarding the output current and voltage and they are cheap, FLSmidth has started to use them in selected applications, like ESP's for soda recovery boilers and non-ferrous processes.

To avoid problems regarding definitions it is important that the TR manufacturers agree upon the information included in the rating plate. Because there are no standards covering this issue, this paper includes suggestions regarding this matter and in this way avoiding confusion in the future [1].

Another issue which is not related directly to the ESP, but to the thyristor controller is the output stage of the firing unit.

Normally the solution has been the use of small pulse transformers in order to provide electrical isolation between the mains and the firing electronics. FLSmidth has developed a novel solution based in the use of optical fibers.

3. Construction and principle of operation

3.1 Construction

In principle the architecture is similar to that of single-phase TR sets. But because the unit is fed from the three-phase mains, the thyristor controller, the HV transformer and the HV bridge rectifier are three-phased as shown in Fig. 1.

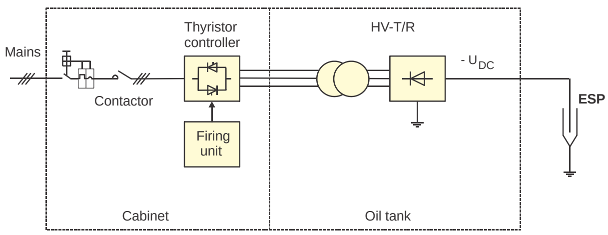


Fig. 1 Block diagram of a three-phase TR set

A three-phase TR set consists of one cabinet and one HV tank, which is also oil cooled with natural convection. As there are 6 current pulses during a period of the line frequency, instead of only 2, and the ESP acting like a capacitive filter, the ripple is much lower. The output voltage can in practice be considered as a pure DC-voltage as seen in Fig. 2.

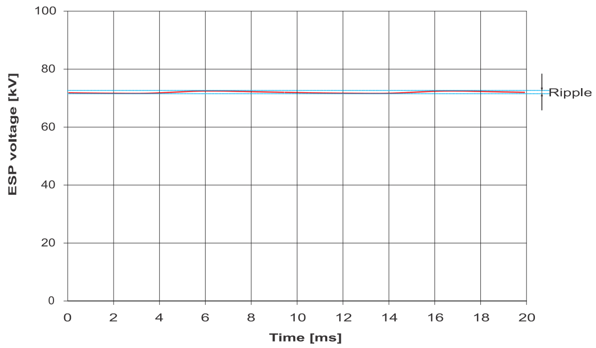


Fig. 2 Waveform of the output voltage

The main waveforms can be obtained by computer simulation or by plant measurements. In order to illustrate the main features of these TR sets simulated waveform will be shown first. Afterwards practical results will be described.

3.2 Principle of operation

In the following is shown the simulation of a 90 kV/1500 mA TR set connected to a 660V mains. The short-circuit voltage is 30%, mainly inductive and obtained with linear chokes. The load is represented by an ESP capacitance of 100 nF and the corona-load by a 2 stage piecewise circuit simulating a corona onset voltage of 37 kV.

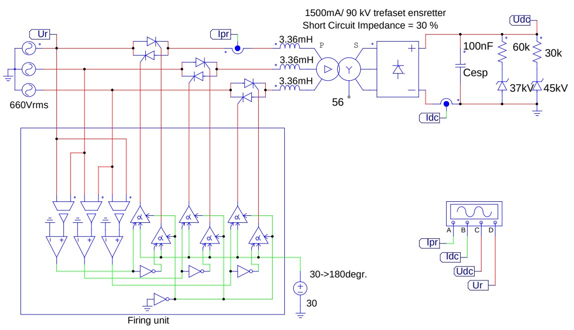


Fig. 3 Simulation circuit of a 1500mA/90 kV three-phase TR set

The results for full load and reduced load are shown in Fig. 4.a and 4.b, respectively.

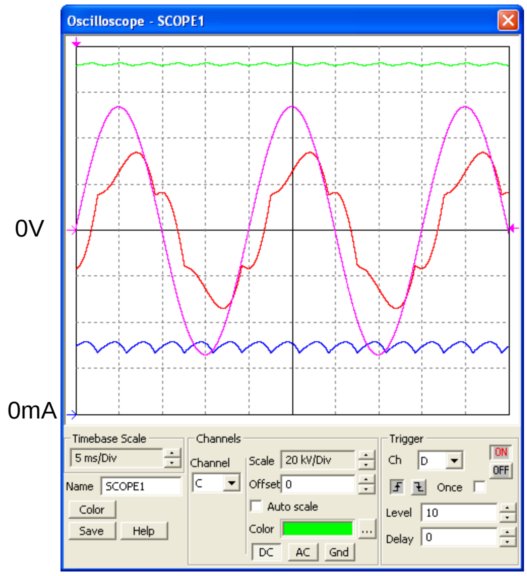


Fig. 4 (a) Waveforms at max. output (α =30˚)

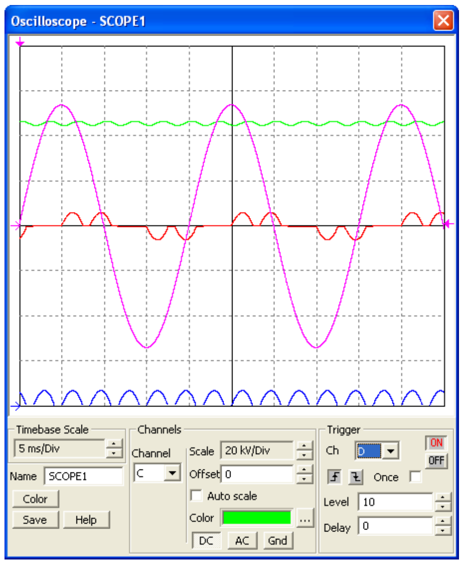


Fig. 4 (b) Waveforms at low output (α =120˚)

From Fig. 4 (a) it can be seen that at α = 30˚ the mean value of the output current is 1500 mA and the mean output voltage is 72 kV. The rms-value of the line

current is 113 A. The firing angle α is normally defined using the line-to-line voltage as reference.

The line current has a waveform resembling a sinus wave, indicating a low harmonic content. Because of the short-circuit inductance the phase current is lagging 55-60˚, the line-to-line voltage and 25-30˚ the line-to-neutral voltage. Assuming a pure sinus waveform the power factor (cosφ) will then be 0.91-0.87, e.g. similar to the one obtained with SMPS units.

When the voltage is reduced by delaying the firing angle, as shown in Fig. 4.b, the output voltage and current are reduced to 47 kV and 200 mA, respectively. It is seen that the voltage is still very smooth, but the line current departs from a sinus wave, indicating an increase in the harmonics.

4. Waveforms in practice

In the following the waveforms corresponding to a 90 kV/600 mA TR set will be shown. This TR set is used in an ESP filtering the dust from a Pierce Smith copper converter and energizes a collecting area of 1500 m^2.

Fig. 5 shows the primary current and ESP voltage at rated ESP current (600 mA). The ESP voltage is very smooth and equal to 72 kV. The primary current has a value of 70.7 A_{rms}. The line voltage is 3*400 V.

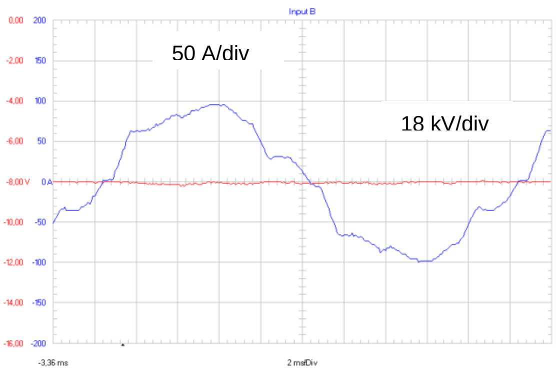


Fig. 5 Primary current (blue) and ESP voltage (red) at rated current.

The same TR was tested at the manufacturer's test rig loaded with 123 kΩ//60 nF. The main waveforms at rated output current are shown in Fig. 6.

The ESP voltage is still very smooth and equal to 72 kV. The measured line current is 70.3 A_{rms}.

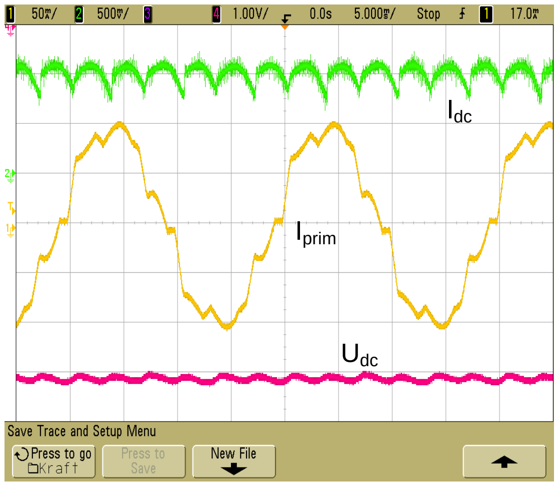


Fig. 6 Primary current (I_{prim}), ESP voltage (U_{dc}) and ESP current (I_{dc}) at rated value (600 mA).

The measured active power is 46 kW and the apparent power 51 kVA giving a power factor of 0.9.

Similar waveforms obtained with RC-load (46 kΩ//60 nF) are shown for a 90 kV/1500 mA TR connected to a 660V line. See Fig. 7 below.

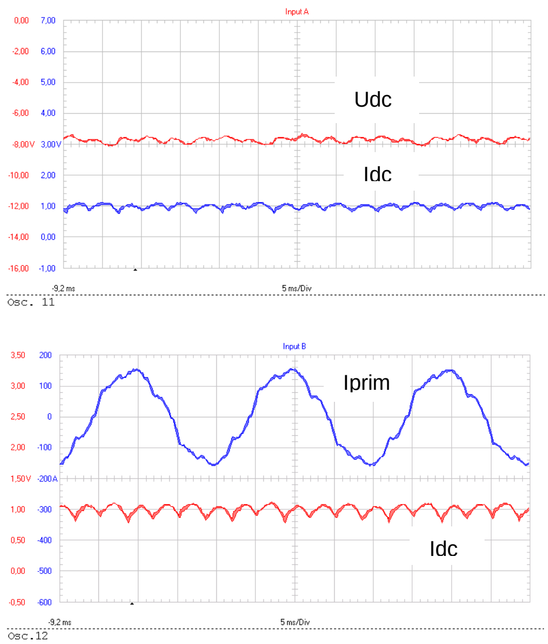


Fig. 7 Main waveforms for a 1500 mA TR at rated ESP current.

The measured ESP voltage is 70 kV and the line current 106 Arms. The measured power factor was 0.87.

4. Main relationships

4.1 Determination of the mean output current

The TR set is chosen for delivering a high current density to a particular ESP field. Then the output current is determined by dividing the current density by the collecting plate area.

4.2 Determination of the mean output voltage

The starting point is the definition of the rated output voltage ($U_{o\ nom}$). For the sake of simplicity FLSmidth uses the peak value of the secondary line-to-line voltage delivered by the transformer at no-load.

For an ideal three-phase rectifier with negligible short-circuit impedance connected directly to the three-phase line, the output voltage is:

$$U_o = \frac{2.34\ U_L}{\sqrt{3}}$$

where U_L is the secondary line-to-line rms-voltage. Using the definition of the rated output voltage we can write:

$$U_o = \frac{2.34 \cdot U_{o\ nom}}{\sqrt{6}} = 0.955 \cdot U_{o\ nom} \qquad (1)$$

But because of the high short-circuit impedance which is mainly inductive, the attainable output voltage at rated current departs significantly from equation (1). Assuming that the voltage loss is caused by the current commutation between phases the result for 30% short-circuit reactance is approximately

$$U_o = 0.80 \cdot U_{o\ nom} \qquad (2)$$

This relationship can be verified by computer simulations and is the design guideline used by FLSmidth. Eq. (2) means that if e.g. an application requires a DC voltage of 80 kV at rated current, the rated output voltage $U_{o\ nom}$ has to be 100 kV.

4.3 Determination of the phase current and installed apparent power

From Fig. 7 it is seen that the output current delivered to the ESP is quite smooth and in principle it can be consider as a pure DC current (I_o). Then the ideal waveform of the current delivered by the secondary winding is as shown in Fig. 8.

$$I_{sec} = \sqrt{\frac{2}{3}} \cdot I_o = 0.816 \cdot I_o$$

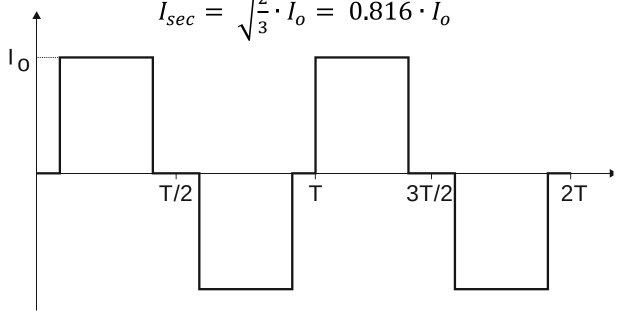


Fig. 8 Ideal waveform of the current delivered by the secondary winding and its rms-value

Then the rms-value of the phase current delivered by the mains can be expressed as:

$$I_L = \sqrt{3} \cdot I_{sec} \cdot n_w = \frac{1}{\sqrt{3}} \frac{U_{o\ nom} \cdot I_o}{U_{mains}} \qquad (3)$$

where n_w is the winding transformation ratio and U_{mains} is the rms-value of the rated voltage of the mains.

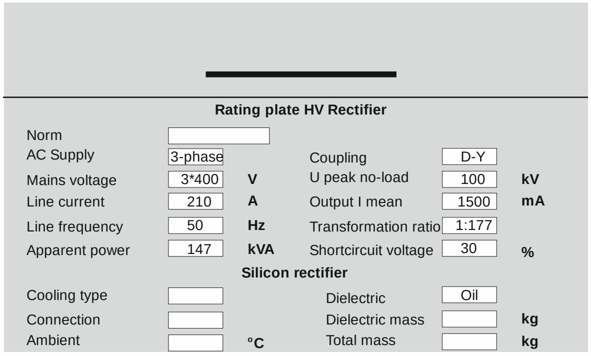
In practice the waveform of the current delivered by the secondary winding has rounded edges so the rms-value will be 3-4% lower than equation (3) giving a corresponding saving in the installed apparent power (S in [kVA]).

The installed apparent power (S) can be readily expressed by:

$$S = \sqrt{3} \cdot I_L \cdot U_{mains} \quad [\text{kVA}] \qquad (4)$$

5. Rating plate

To avoid interpretations regarding the capabilities of a particular three-phase TR set, it is important that the unit is marked in a correct manner, so all the important data needed is available on the rating plate [1]. Based on above section our suggestion to the TR set manufactures is the one shown below.



Rating plate HV Rectifier

Norm					
AC Supply	3-phase		Coupling	D-Y	
Mains voltage	3*400	V	U peak no-load	100	kV
Line current	210	A	Output I mean	1500	mA
Line frequency	50	Hz	Transformation ratio	1:177	
Apparent power	147	kVA	Shortcircuit voltage	30	%

Silicon rectifier

Cooling type			Dielectric	Oil	
Connection			Dielectric mass		kg
Ambient		°C	Total mass		kg

Fig. 9 Suggestion for data to be included on rating plate.

A definition of the main parameters that should be shown on the rating plate is included in the following:

Mains voltage [V_{rms}]:

Defined as the rated line-to-line voltage the T/R set is connected to.

Upeak no-load [V_{peak}]:

Defined as the peak value of the secondary line-to-line voltage at no-load, when the rated mains voltage is applied to the primary windings.

Line current [A_{rms}]:

Defined as:

$$I_L = \frac{0.97}{\sqrt{3}} \frac{U_{o\,nom} \cdot I_o}{U_{mains}} \qquad (5)$$

(for 30% short-circuit voltage)

Output I mean current (mADC):

Defined as the mean current that can be delivered by the T/R set to the ESP load.

Transformation ratio n:

Defined as the turns ratio of the HV transformer. This is normally Δ-Y connected.

Short-circuit voltage e_{SC} [%]:

Defined as the RMS primary voltage necessary for obtaining the rated line current when the output of the TR is short-circuited (typically 30%).

Rated apparent power [kVA]:

Defined as: $S = \sqrt{3} \cdot I_L \cdot U_{mains}$

Table 1 illustrates the results when applying eq. (5) and (2). These are compared with the values measured for Fig. 5 and 7 (in parenthesis).

3-phase TR set	1500 mA/90kV	600 mA/90 kV
Mains voltage [V_{rms}]	3*660	3*400
Line current [A_{rms}]	114 (106)	75.6 (71)
Output voltage [kV]	72 (70)	72 (72)

Table 1. Calculated and measured values

6. Application example

In the following, results obtained on a retrofit for a low resistivity application will be given.

The ESP consists of 4 chambers in parallel with 3 fields in series, having a collecting area of 1980 m^2. The duct spacing is 300 mm. The ESP filters the gases coming from a recovery boiler with a flow of 774.000 Nm^3/h. The gas temperature at the outlet is 200 ˚C and the dust emission is normally 150 mg/ Nm^3. The upgrading of the ESP consisted in mechanical improvement of the internals and the replacement of the old single-phase TR's by 1500 mA/ 90 kV three-phase TR's.

Measurements before and after the refurbishment of the installation were made for the sake of comparison. These are shown in Table 2.

Chamber		Inlet	Center	Outlet
1	Before:	14 kW	21 kW	41 kW
	After:	9 kW	85 kW	81 kW
2	Before:	6 kW	31 kW	50 kW
	After:	3 kW	70 kW	81 kW
3	Before:	5 kW	18 kW	54 kW
	After:	4 kW	36 kW	87 kW
4	Before:	8 kW	40 kW	47 kW
	After:	17 kW	98 kW	80 kW
Total P_{cor}	Before:	33 kW	110 kW	192 kW
	After:	33 kW	289 kW	329 kW

Table 2. Main results obtained after upgrading of the ESP installation.

Table 2 shows that the corona power was increased from 335 kW to 651 kW, causing a reduction in the particulate emission from 102 to 22 mg/Nm^3. It is seen that the corona power was not increased in the inlet fields, but a drastic increase was observed in the center and outlet fields, leading to this considerable reduction in the dust emission. The working point in the center and outlet fields was moved to higher values, and at the outlet fields the TR's operated at rated ESP current.

The inlet dust concentration and treated gas flow is the same in both cases.

The TR's are energized from a 3*660 V/50 Hz mains. This high voltage level doesn't cause any trouble. This is not the case when using SMPS units.

After an introduction without teething troubles, by the time being FLSmidth has sold 177 units. The largest one being a 4300 mA/100V unit, but 2800 mA, 3300 mA and 3400 mA units are not uncommon.

7. Novel firing unit

Normally the 6 firing pulses needed are delivered by 6 output stages. This required an independent DC power supply (+U) and 6 pulse transformers providing electrical isolation between the mains and the electronic circuits. Se Fig. 10.

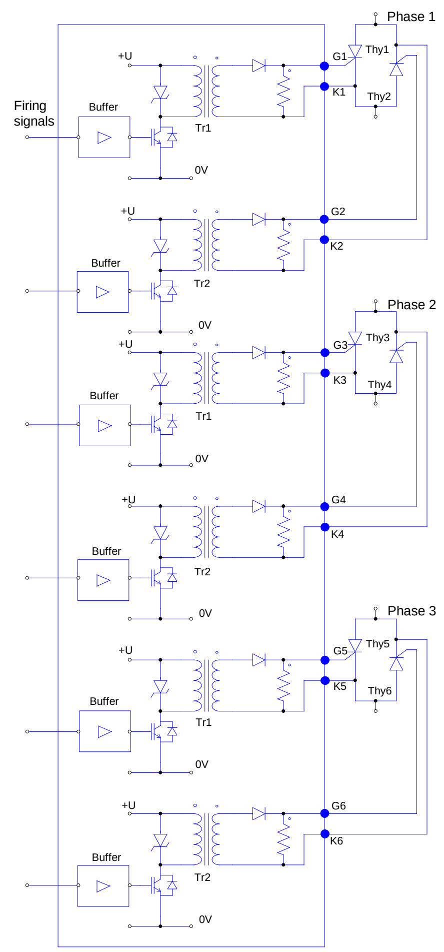


Fig. 10 Traditional firing with 6 output stages.

In principle the use of optical fibers will provide a better electrical isolation and if the power supply +U can be eliminated, then a better solution can be achieved.

Such a solution is depicted in Fig. 11, but only one phase is shown.

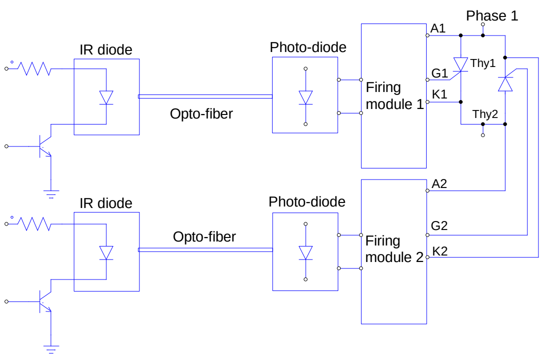


Fig. 11 Solution with optical fibers

Fig. 11 shows that the photo-diode transmits the firing command to a firing module, which is feeded by the forward blocking voltage applied to the thyristor before they are fired. When the thyristors are on its ON-state the voltage supply of the module disappears.

The only problem with this solution is the cost, as it requires 6 transmitters, 6 receivers, 6 optical fibers and 6 modules. But using a diode bridge and sending the firing pulse to both thyristors, simultaneously, twice in one period of the line frequency, the number of components is reduced to one half. The solution is based in the fact that the thyristor which is in the reverse blocking state will not be turned on in spite a firing pulse is applied to its gate. Fig. 12 shows this solution, where only one of the three phases is shown.

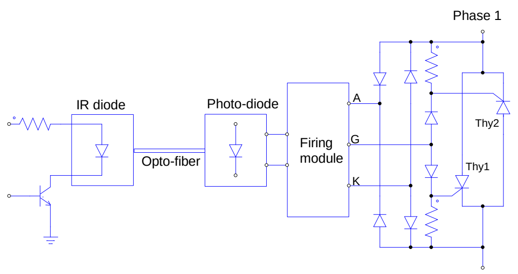


Fig. 12 Solution with only one firing module per phase.

Obviously, this solution can also be used in firing the 2 antiparallel thyristors comprised in a single-phase TR set.

8. Conclusions

The use of three-phase TR sets in low resistivity application has a number of advantages. Among them, the following can be mentioned:

- It can provide a smooth ESP voltage leading to a higher corona power and therefore a lower particulate emission in low resistivity applications.
- A three-phase TR is a symmetrical load and provides a very high power factor of about 0.9.
- There is no practical limitation in rated current and voltage. FLSmidth has 2800-3400 mA units in operation. TR manufacturers can delivere larger units like 4000 mA/140 kV without hesitation.
- There is no problem in energizing three-phase TR's from e.g. a 3*690 V_{rms} mains.
- Regarding prices, if we compare a 2800 mA/100 kV unit with the corresponding single-phase TR, the three-phase TR is only 30 % more expensive. The same is the case if we compare 1000 mA/140 kV units.
- The rugged and well-proven construction has turned up to be be very reliable. No mayor problems have been experienced.

Regarding disadvantages, we can mention the well-known ones, like:

- Higher weight and volume.
- Need of a control cabinet and place in the switch-gear room.
- Need of a power cable between control cabinet and TR set.

9. References

[1] V. Reyes. 'Demystifying the rating plate of T/R sets'. ICESP IX Conference. South Africa. May 2004.