Application of multi-phase HV rectifiers in electrostatic precipitators

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Abstract This paper describes the use of the novel multi-phase high voltage (HV) transformer-rectifiers (TR) in ESP applications, as an alternative to high frequency switch mode power supplies (HFPS). As well-known a three-phase TR can deliver a very smooth voltage waveform. This power supply has the disadvantage of not being able to deliver a pulsating voltage waveform (high ripple) in case a change in the operating conditions requires it. A multiphase HV power supply based on a traditional three-phase power supply can eliminate this shortcoming as with an ingenious switching in the primary side of the HV transformer and in the thyristor controller, both single-phase (high ripple) and three-phase operation (low ripple) are possible. This paper describes the switching principles as well as the output power which is possible to achieve in both operation modes. The multi-phase TR has been tested at full-scale in an ESP for coal-fired boiler and the first commercial installation has been commissioned.

1. Introduction

In the electrical energization of ESP's by the time being are found following HV power supplies:

- Single phase TR (1-phase TR),
- Three-phase TR (3-phase TR),
- HF switched mode supply (HFPS),
- MF switched mode supply (MFPS),
- Micro-pulse system (MPS).

The main feature characterizing each power supply is the voltage waveform delivered to the ESP load. This has to be suitable to the nature of the particulate treated by the ESP. In simple terms, an increasing dust resistivity requires a more pulsating voltage waveform (high d*v*/d*t*).

A. Single phase TR [1]

They can deliver a voltage with high ripple of tens of kV (100/120 Hz). They can also operate in the so-called intermittent energization mode (IE), where the current pulses delivered to the ESP are blocked by an even number of half-periods (2, 4, 6, etc).

B. Three-phase TR [2]

They can deliver a voltage with very low ripple (few kV) having a frequency of 6 times the line frequency, i.e. a very smooth voltage waveform.

C. HF switched mode power supply [3]

They are also intended to provide a very smooth voltage waveform, but they can also operate in the IE-mode. The switching frequency is in the range 20-30 kHz.

D. MF switched mode power supply [4]

They are also intended to provide a very smooth voltage waveform, but here the switching frequency is in the range 200-400 Hz. IE-mode is also possible.

E. Micro-pulse system [5]

They can deliver narrow HV pulses (60-140 µs) superimposed on a smooth base voltage (40-60 kV). The HV pulses are repeated with a frequency typically in the range 1-200 pulses/s).

Besides the above-mentioned power supplies FLSmidth has recently introduced a new one, the multiphase power supply (MPPS). The MPPS combine a 3-phase TR and a 1-phase TR in one unit, based on a standard 3-phase TR set. In the following it will be described the principle of operation and the output voltage and current that can be obtained on an ESP load.

2. Construction and principle of operation

2.1. Construction

The basic unit, the three-phase HV power supply consists of one control cabinet and one HV tank, which is oil-filled cooled by natural convection. This power supply is fed from the three-phase mains and comprises a thyristor controller, a HV transformer and a HV bridge rectifier as shown in Fig. 1.

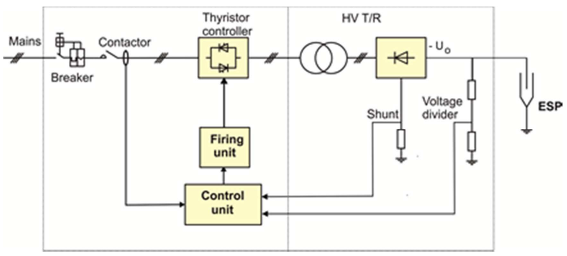


Figure 1. Block diagram of a three-phase TR set

As there are 6 current pulses during a period of the line frequency, instead of only 2, and as the ESP acts like a capacitive load, the ripple is much lower. The output voltage can in practice be considered as a pure DC-voltage as seen in Fig. 2.

The ESP voltage has negative polarity as ESP's work normally with negative corona. In Fig. 2 is also shown the corresponding waveform delivered by single-phase TR's.

The problem to solve is how to switch between both modes of operation, in the following called 1-phase and 3-phase operation.

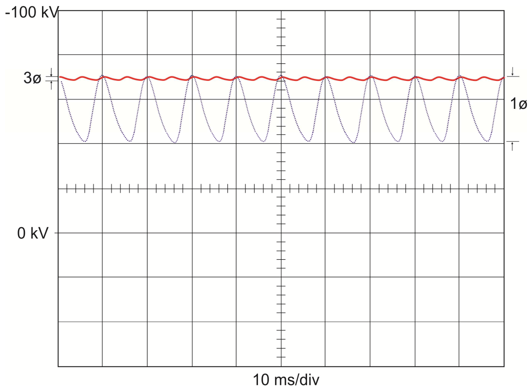


Figure 2. Waveform of the output voltage

2.2. Principle of operation

In principle the conversion from 3-phase to 1-phase operation can be implemented as shown in Fig. 3a. Here it is seen that the three-phase transformer (Δ-Y coupling) is energized directly from a 3-phase line (ABC).

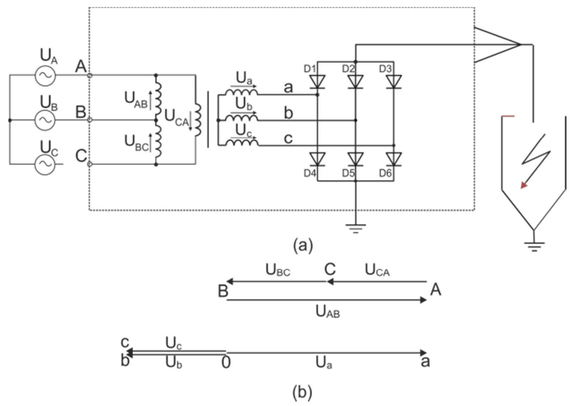


Figure 3. Conversion principle for 1-phase (high ripple) operation

Fig. 3a shows that the main change is the interruption of phase C in the primary side of the HV transformer. In Fig. 3b is shown the corresponding phasor diagram for the voltage across each primary winding (Δ-connection). It is seen that the winding voltage U_{BC} and U_{CA} are in phase and equal and their amplitude is ½ of U_{AB} and have an opposite phase, i.e. they are shifted 180˚ in relation to U_{AB}.

On the secondary side the phase voltages $U_b = U_c = ½\ U_a$. As shown, U_b and U_c are equal and in phase, but shifted 180˚ in relation to U_a.

Then points ‘b’ and ‘c’ of the three-phase bridge rectifier has the same potential. In other words the bridge rectifier behaves as a single-phase bridge rectifier fed with a single-phase voltage of $1.5{\cdot}U_a$.

In practice, the voltage applied to the primary windings is controlled by a thyristor controller, so a number of other changes must be introduced.

In Fig. 4 is shown the changes when considering the thyristor three-phase controller comprising thyristor modules T_A, T_B and T_C.

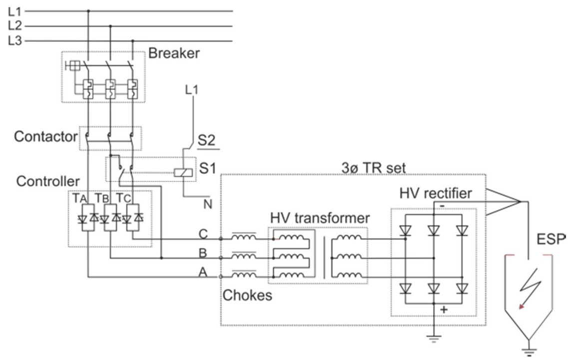


Figure 4. Changes in primary side for single-phase operation

As seen, it is required to include a contactor S1 which coil is e.g. energized from one phase. S1 has two set of contacts. The shown position corresponds to normal three-phase operation where all 3 thyristor modules TA, TB and TC are connected to the industrial mains (L1, L2, L3). When the change-over is performed by de-energizing S1’s coil via switch S2, then phase C is interrupted, the thyristor module TB is short-circuited so only TA is active thus activating single-phase operation.

Other changes related to the firing of the thyristors and in the software of the control unit have to be performed. But this can be performed in different ways depending of the firing unit used for single phase TR’s and for three-phase TR’s, respectively. One example will be given later in § 6.

The conversion to single-phase (high ripple) operation has been first tested at the laboratory in a 4.2 kV/1350 mA three-phase TR model. Thereafter, the next test was on a pilot ESP using a 125 kV/35 mA three-phase TR at a sintering plant.

Both tests gave successful results, so the final step was a full scale test performed in a power plant. This test is shortly described below.

3. Full scale test

As seen in Fig. 5 a three-phase TR with rated values 110 kV/1400 mA (30% short-circuit voltage) connected to 3×400 V line was mounted at the inlet field of one chamber of the FLSmidth ESP installed at a power plant in Copenhagen, after removing the original single-phase TR.

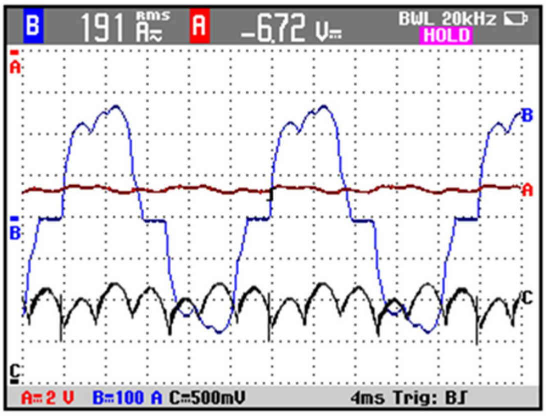
At full load (250 MW) the gas flow is 315 m^3/s and the inlet temperature 127 ˚C.

Figure 5. 3-phase TR used in full scale test

3.1. Three-phase operation

The waveforms in this case are the normal ones for this operation mode [2]. In Fig. 6a are shown typical waveforms for normal operation and in Fig. 6b operation at spark.

a)



b)

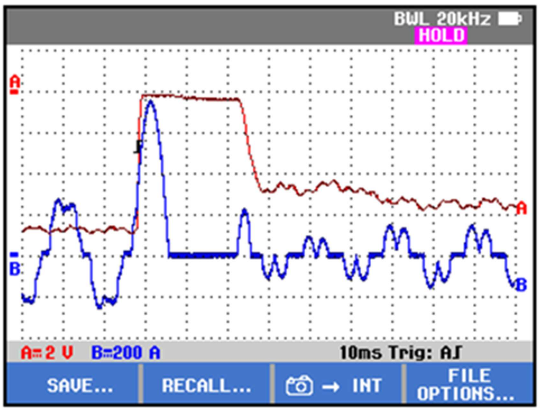


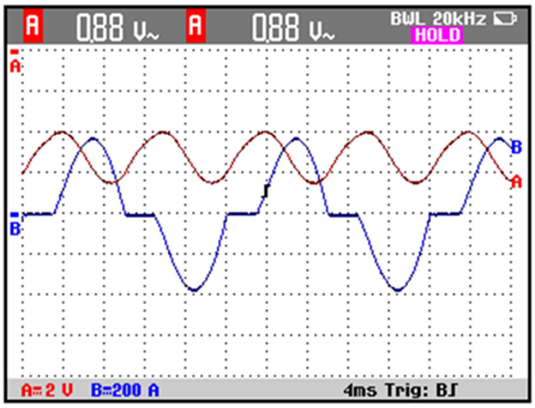
Figure 6. a) Primary current (blue), ESP voltage, (red) and ESP current (black) at 50% boiler load,
b) Primary current (blue) and ESP voltage, (red) at 100% boiler load and spark. $I_{DC} = 1400$ mA;
$U_{DC} = 74$ kV; $I_{Pr} = 191$ A; $\alpha = 85^\circ$

As explained in § 5.1 the TR set could deliver an output voltage of 88 kV, but the rated current of 1400 mA is already reached at 74 kV due to the current-voltage characteristic (CVC) of the ESP field. Therefore there are some dead zones in the primary current waveform. Fig. 6b shows the voltage recovery after spark. After a 20 ms blocking time the voltage is recovered in approximately 10 ms.

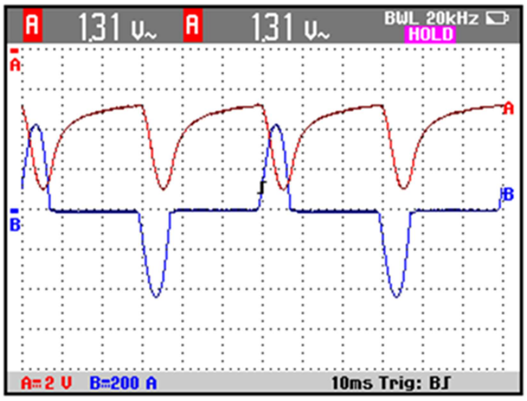
3.2. Single-phase operation

The waveforms for normal DC-operation are shown in Fig. 7a. In Fig. 7b and Fig. 7c are shown waveforms with IE-operation (degree of intermittence $N_{ec} = 3$ and 5).

a)



b)



c)

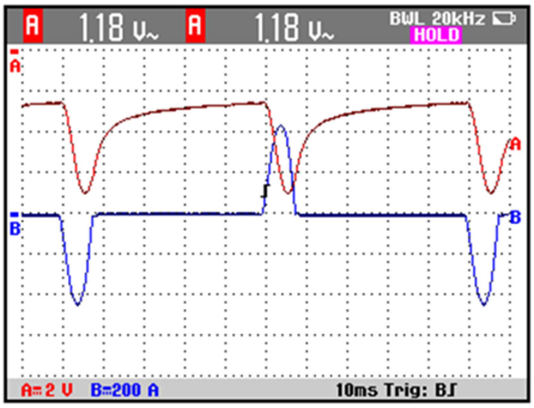


Figure 7. Waveforms in single phase operation: a) DC operation at 50% boiler load, b) IE operation ($N_{ec} = 3$) at 50% boiler load, c). IE operation ($N_{ec} = 5$) at 50% boiler load

The values obtained in each operation mode are shown in Table 1.

Table 1. Operation values at 1ø-mode

N_{ec}	1	3	5
I_{DC} [mA]	1000	450	280
U_{DC} [kV]	58	44	39
U_{DCmin} [kV]	45	32	29
U_{DCmax} [kV]	77	77	77
I_{pr} [A]	224	156	113
α [˚]	56	40	40

Fig. 8 shows the voltage recovery after spark, where the voltage is recovered without need of blocking periods.

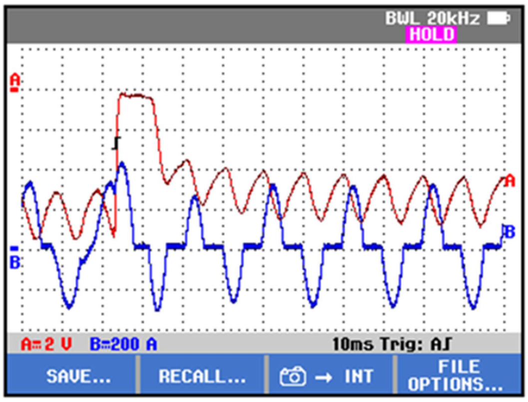


Figure 8. Waveforms at 100% boiler load. Operation values: I_{DC} = 810 mA; U_{DC} = 68 kV; U_{DCmin} = 56 kV; U_{DCmax} = 82 kV; α = 40°

As seen in Fig. 7 and in Fig. 8, the waveforms delivered by the three-phase TR set for single-phase operation are as expected for a single-phase TR. The output values are also as expected, but later it will be explained what the expected attainable values in single-phase operation are.

Comparing Fig. 6 with Fig. 7 and the values in Table 1, it is clear that is not possible to get the same ESP current in both operation modes and therefore, the attainable corona power in 1-phase operation is lower.The reason for that will be explained in one of the following sections.

3.3. Current-Voltage Characteristics (CVC)

Now using the multi-phase approach it is possible in an easy way to compare the CVC's valid for single- and three-phase operation. These are shown in Fig. 9.

Fig. 9 shows that the CVC's obtained in 1-phase and in 3-phase operation are almost coincident. But, in 3-phase operation is possible to operate at rated current (1400 mA or 0.47 mA/m^2) without spark. This is not the case when operating in 1-phase mode, where sparking takes place at about 900-1000 mA. This was also the case with the original single-phase TR (110 kV/1000 mA).

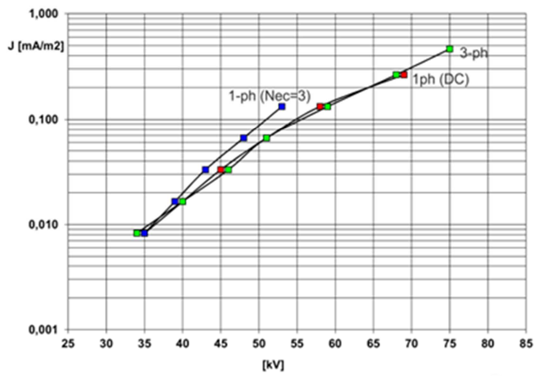


Figure 9. CVC's with 1-phase and 3-phase operation

4. Output power

The output power will depend on the attainable output current and voltage in both modes of operation. These two magnitudes are interrelated by the existing CVC at that particular moment.

4.1. Three-phase operation

According to [2] the attainable output voltage at rated current is approximately:

$$U_{o3ø} = 0.8 \cdot U_{nom} \qquad (1)$$

where U_{nom} is defined as the peak-value of the secondary line-to-line voltage, at no-load. (E.g. in the test TR, $U_{o3ø} = 0.8 \cdot 110 = 88$ kV).

4.2. Single-phase operation

4.2.1. Output current

The limitation here is not to exceed the rated primary phase current delivered by the mains. The relationship between the primary phase current and the output mean current can be derived from Fig. 10.

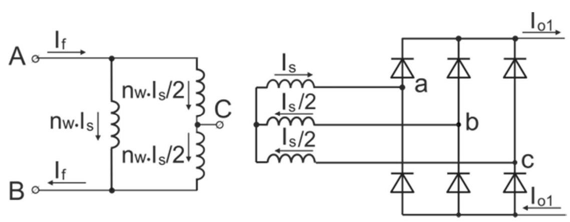


Figure 10. Current relationships in single-phase operation

The terminals 'b' and 'c' in the secondary windings are at same potential, so the current through winding 'a' (I_s) returns as ½·I_s in windings 'b' and 'c'. The winding transformation ratio is n_w. Then, the currents through the primary windings are:

$$I_{wA} = n_w \cdot I_s \qquad (2)$$

$$I_{wB} = I_{wC} = 0.5 \cdot n_w \cdot I_s \qquad (3)$$

Assuming that the output DC current I_{o1} has a form factor FF ≈ 1.35, then:

$$I_s = FF \cdot I_{omean1} \tag{4}$$

where I_{omean1} is the output mean current.

From eq. (2), (3) and (4),

$$I_{wA} = FF \cdot n_w \cdot I_{omean1} \tag{5}$$

$$I_{wB} = I_{wC} = 0.5 \cdot FF \cdot n_w \cdot I_{omean1} \tag{6}$$

Then the primary phase current in single-phase operation can be expressed as:

$$I_{f1} = I_{wA} + I_{wC} = 1.5 \cdot FF \cdot n_w \cdot I_{omean1} \tag{7}$$

The primary phase current in three-phase operation can be expressed as:

$$I_{f3} = \sqrt{3} \cdot n_w \cdot I_s = \sqrt{3} \cdot n_w \cdot \sqrt{\frac{2}{3}} \cdot I_{onom}$$

$$I_{f3} = \sqrt{2} \cdot n_w \cdot I_{onom} \tag{8}$$

where I_{onom} is the rated output current of the 3ø TR set.

Then because $I_{f1} = I_{f3}$ from (7) and (8) and for FF = 1.35:

$$\frac{I_{omean1}}{I_{onom}} = \frac{\sqrt{2}}{1.5 \cdot FF} = 0.698 \tag{9}$$

So in theory, in single-phase operation the attainable output mean current is about 70% of the rated current in three-phase operation. But from Fig. 10 it can be demonstrated that the primary winding current in single- phase operation is about 1.15 times larger than in three-phase operation (for FF = 1.35). Therefore, if the primary winding is not oversized considering this factor, the output current has to be reduced accordingly.

This means that the maximum attainable output current in this case will be:

$$I_{1max} \approx 0.6 \cdot I_{onom} \tag{10}$$

Anyhow, a more precise calculation can be performed by computer simulation, where all conditions like existing CVC, ESP field capacitance, TR data, etc. are taken into consideration.

4.2.2. Output voltage

The main reason for the lower attainable output current is that the input AC voltage to the bridge rectifier is less in single-phase operation.

Ideally in three-phase operation this voltage is:

$$U_{in3} = \sqrt{3} \cdot n_w \cdot U_{mains}$$

and as explained in § 3.2 in single-phase operation this voltage is:

$$U_{in1} = 1.5 \cdot n_w \cdot U_{mains}$$

So

$$\frac{U_{in1}}{U_{in3}} = \frac{1.5}{\sqrt{3}} = 0.866.$$

Supposing that the attainable output voltage at rated current is typically $0.67 \cdot U_{onom1}$ and now U_{onom1} is only $0.866 \cdot U_{onom}$, then the attainable output voltage is:

$$U_{o1} = 0.67 \cdot 0.866 \cdot U_{nom} = 0.58 \cdot U_{nom} \tag{11}$$

4.3. Results with computer simulation

The output characteristic can be obtained by loading the TR set with different CVC's and applying the mains voltage directly to the primary windings [1]. As an example the slope of the CVC will be maintained and the curve will be displaced to higher voltages by changing the corona onset voltage. The results are shown in Table 2 and the curve $U = f(I)$ is plotted in Fig. 11.

Table 2. Output characteristic $U_o = f(I_o)$

	Case	U_o [kV]	I_o [mA]	I_f [A_{rms}]
A	U_{co} =25 [kV]	68.3	962	218
B	U_{co} =30 [kV]	69.4	875	201
C	U_{co} =35 [kV]	70.5	790	184
D	U_{co} =40 [kV]	71.7	705	167

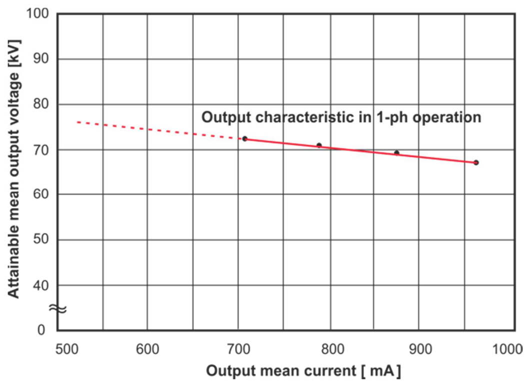


Figure 11. Output characteristic for a 1400 mA/ 110 kV three-phase TR set

Fig. 11 shows how the output voltage increases and the output current decreases with increasing corona onset voltage. In Fig. 12 is shown the simulation result for case A (U_{co} = 25 kV). For the sake of simplicity, the output voltage is shown as positive going.

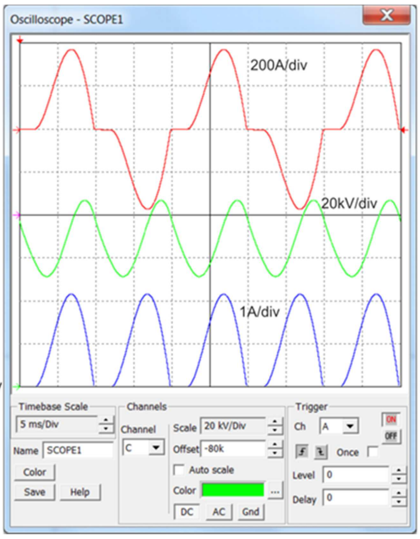


Figure 12. Example of simulation result for case A ($Uco = 25$ kV)

In Fig. 13 is shown an example of a possible implementation. This corresponds to the case where a 3-phase firing PCB is used for firing the thyristors in a 3-phase TR and a 1-phase firing PCB is used for firing a 1-phase TR.

In other cases there exist only one firing PCB, which is used together with a 1-phase TR and 3 of them are used in case of 3-phase TR's.

The key components are the switch S11, the auxiliary relays Q3ø and Q1ø, and the main contactors Q01 and Q03 with their respective energizing coils.

When S11 is in position 1 then the contactor Q03 is energized and normal three-phase operation is achieved. In position 2, Q01 is energized so phase L3 is disconnected and module TB is short-circuited, allowing 1-phase operation.

5. Practical implementation

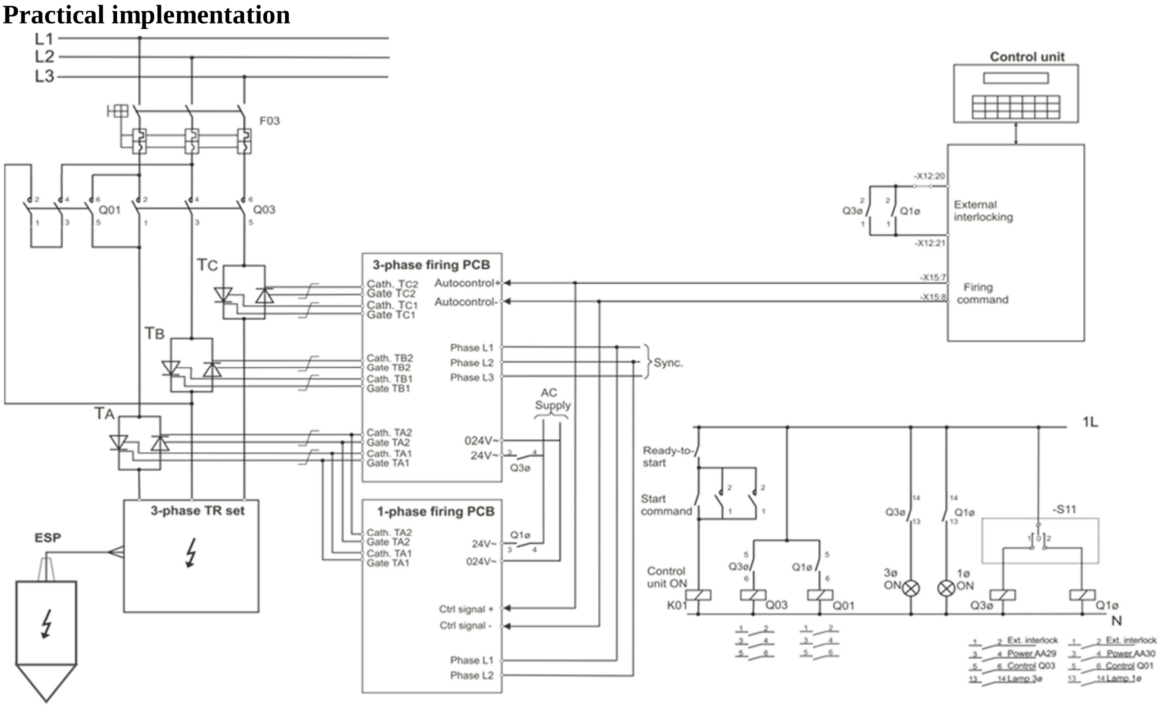


Figure 13. Example of practical implementation

6. Conclusions

The use of multi-phase power supply (MPPS) 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 in low resistivity applications.
- It can provide a high ripple like a single-phase TR in process where this waveform is beneficial, e.g. in medium resistivity applications.
- It can provide operation in IE-mode, e.g. in higher resistivity applications.
- There is no practical limitation in the rated output current and voltage, compared e.g. with HFPS's.
- There is no problem in energizing multi-phase TR's from e.g. a 3·690 V_{rms} mains.
- Regarding prices, a corresponding multi-phase TR is not more expensive than a corresponding three-phase TR.
- The rugged and well-proven construction is very reliable. No problems have been experien-ced.
- Regarding disadvantages, we can mention the well-known ones of 3-phase TR's, like:

- Higher weight and volume.
- Need of a control cabinet and place in the switch-gear room.
- The output mean current in 1-phase operation is limited to a value just below 60% of the rated mean current. This is not a major problem as in single phase operation is not possible to get the same output current due to spark occurrence. Furthermore, single-phase operation is demanded in cases of increasing resistivity and this calls for lower ESP-current due to back-corona.

References

[1] Reyes V., ICESP IX Conference, South Africa, 2004.
[2] Reyes V., Poulsen K., ICESP XIII Conference. Bangalore, India, 2013.
[3] Reyes V., Wallgren B., ICESP VII Conference, Kyongju, Korea, 1998.
[4] Grass N., Kloeckner M., ICESP XII Conference, Nuremberg, Germany, 2011.
[5] Reyes V., Elholm P., ICESP XII Conference, Nuremberg, Germany, 2011.