Demystifying the rating plate of T/R sets

by
Victor Reyes
FLS Airtech A/S
Denmark

Abstract

When working with retrofit projects some data for the T/R set that is not possible to find on the rating plate is often needed. Sometimes the rated voltage is indicated in a way that it can be interpreted wrongly. This leads often to mistakes and time wasting. In other cases, e.g. by operational problems, the performance of the T/R set needs to be assessed and again, the ESP manufacturer needs the relevant information.

Because of the lack of uniformity among T/R set manufacturers in marking their product, this paper explains the type of electrical information that should be indicated on the rating plate as a minimum requirement. The reason for that is illustrated with different examples, where the T/R set operates with different loads.

1. Introduction

The way the T/R sets have been marked over the years has been determined by the manufacturers and not by the users' needs, i.e. ESP manufacturers and end-users. The results is a confusing kaleidoscope based mainly on the company culture and tradition that unfortunately has prevailed during the last decades, and it has only changed sometimes due to the ESP suppliers' requirements, and sometimes from the consulting engineers used by the client for a particular project.

Unfortunately the result can be very confusing for the end-user and for the ESP-manufacturer, especially in case of retrofit projects. In this case the main problem is to find the correct data from the rating plate, in order to calculate theoretically the capabilities of the installed old T/R set. In the last decades computer simulation programs have been available, making it possible to assess the performance of a particular T/R set loaded by a particular ESP field. In the past, this was not possible and often the only way to do this was by direct measurements on site.

In other cases and in relation to a new project, the ESP manufacturer is confronted with some unclear and demanding requirements regarding T/R set marking from the consulting engineer used by the client.

Because of the diversity found in this field and the time wasting involved in it, mainly due to a lack of understanding from the different actors involved in this process, the author has the opinion that this situation needs to be clarified. After such a clarification, it is the author's hope that the ideas presented in this paper can lead to a norm that will greatly simplify the daily work, not only for the ESP manufacturers, but also for the consulting engineers and the end-users, and hopefully for the T/R set manufacturers.

2. Important parameters in the description of a T/R set

A T/R set is depicted in Fig. 1.

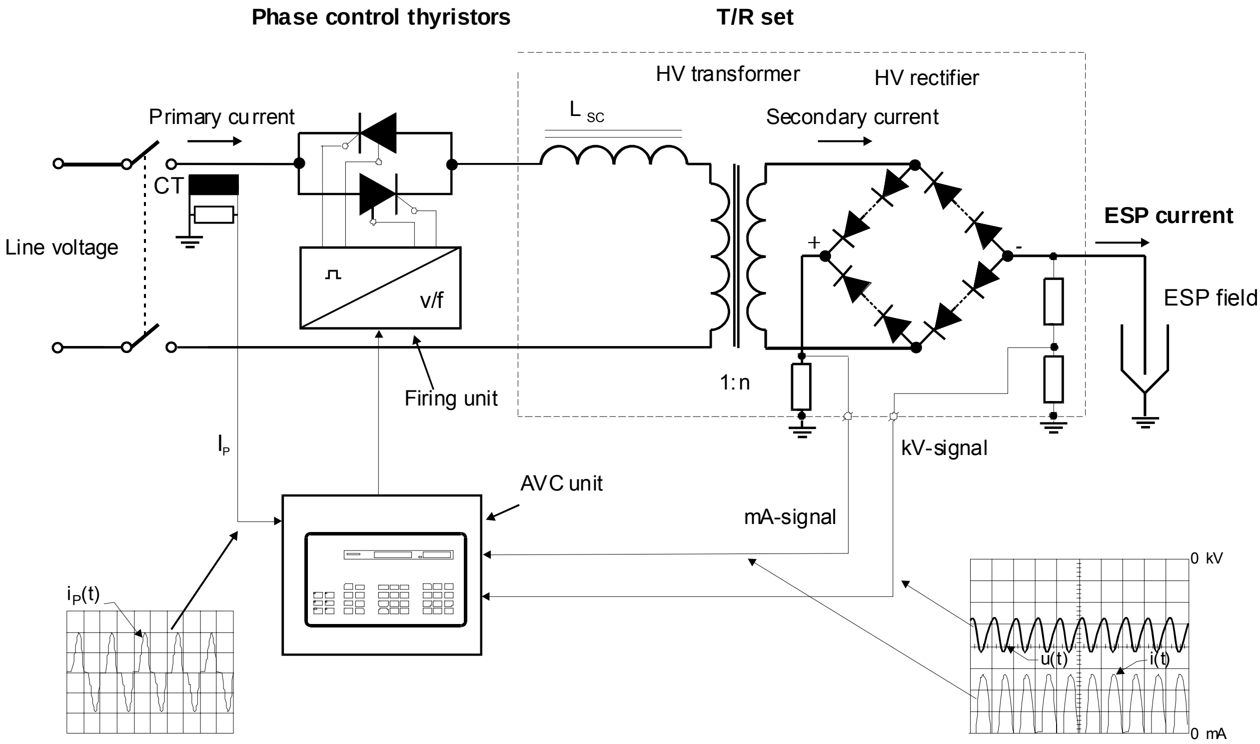


Fig. 1 Block diagram of a T/R set

From the above block diagram it appears that the T/R set mainly consists of a HV transformer and a HV rectifier. In order to assess its performance some important data for the HV transformer is needed. One important problem arises from the fact that the ESP current and the primary current have to be limited in case of sparks, arcs and short-circuits inside the ESP. The solution used by T/R manufacturers is to include extra inductance on the primary side of the HV transformer normally named Current Limiting Reactor (CLR). A common used value for this impedance is equivalent to a short-circuit voltage of 30-40%.

The Europeans usually include this impedance inside the oil tank as shown in Fig. 1, while the Americans often include it inside the control cabinet. Furthermore, it is common that this linear choke has tappings, which are equivalent to saying that different inductance values can be chosen, which are normally marked on the linear choke.

But independently of this problem the rating plate of the T/R set, besides the rated primary current and primary voltage, should include the transformation ratio (n) of the HV transformer and the short-circuit impedance of the TR-set (e_{sc}). The latter has normally an inductive nature, so the main issue here is to determine the value of the series inductance in the primary side. In case of extra impedance is included in series as a linear reactor inside the T/R set, this should be marked accordingly. In case the linear reactor is included in the control cabinet, the rating plate should only include the short-circuit voltage drop of the HV transformer alone.

A definition of the main parameters to be defined and that should be included in the rating plate are the following:

Rated primary voltage $U_{P\text{-}RMS}$ [V_{RMS}]:

Defined as the rated line voltage ($U_{L\text{-}RMS}$) the T/R set is connected to.

Rated primary current $I_{P\text{-}RMS}$ [A_{RMS}]:

Defined as the rated primary RMS current of the T/R set to be delivered by the mains.

Transformation ratio n:

Defined as the turns ratio of the HV transformer.

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

Defined as the necessary RMS primary voltage for obtaining the rated primary current when the T/R output is short-circuited.

Output mean current $I_{O\text{-}mean}$ (mADC):

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

By knowing these values the electrical performance of the T/R set can be evaluated 100%. This means that other important magnitudes can be determined by calculation or computer simulation.

For instance, the following magnitudes can be determined by direct calculation:

Rated secondary RMS no-load voltage U_S [kV_{RMS}]:

This is the secondary RMS voltage delivered by the HV transformer at no-load:

$$U_{So\text{-}RMS} = n \cdot U_{P\text{-}RMS} \qquad (1)$$

Secondary peak no-load voltage $U_{0\text{-}peak}$ [kV_{RMS}]:

This is the secondary peak voltage delivered by the HV transformer at no-load:

$$U_{o\text{-}peak} = n \cdot \sqrt{2} \cdot U_{P\text{-}RMS} = \sqrt{2} \cdot U_{So\text{-}RMS} \qquad (2)$$

Rated form factor of the ESP current:

This is equal to the relationship between the RMS-value and the mean value of the ESP current, i.e.

$$FF = I_{O\text{-}RMS} / I_{O\text{-}mean} \qquad \text{or}$$

$$FF = I_{P\text{-}RMS} / (n \cdot I_{O\text{-}mean}) \qquad (3)$$

Because of the ESP load, the waveform of the ESP current is not a sinus wave (FF=1.11) its form factor is greater and a typical value is about 1.4. If the manufacturer has not indicated its value, the form factor can be calculated from eq. (3).

Value of series inductance L_S:

From the definition for the short-circuit voltage e_{SC} one may write:

$$U_{P\text{-}RMS} \cdot e_{SC} = I_{P\text{-}RMS} \cdot X_{LS}$$

$$X_{LS} = \omega \cdot L_S = U_{P\text{-}RMS} \cdot e_{SC} / I_{P\text{-}RMS}$$

and then

$$L_S = \frac{U_{P-RMS} \cdot e_{SC}}{I_{P-RMS} \cdot \omega} \qquad (4)$$

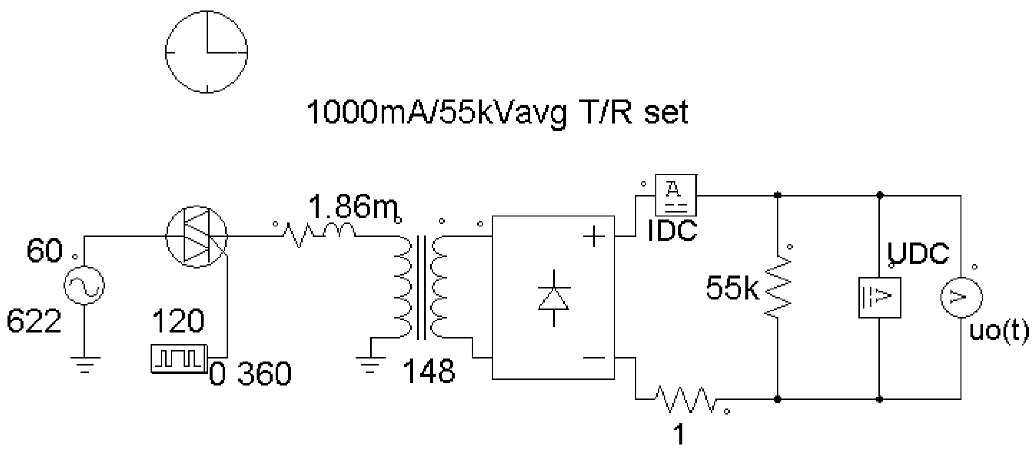
3. Differences in the American and European rating plates

Generally speaking the main problem is that the T/R set manufacturers do not indicate the transformation ratio (**n**) in an explicit way. The other lack of information is the short-circuit voltage of the T/R set. Another problem may be the form factor (FF) used by the T/R set manufacturer in its design, which in some cases can be 1.2 instead of 1.4.

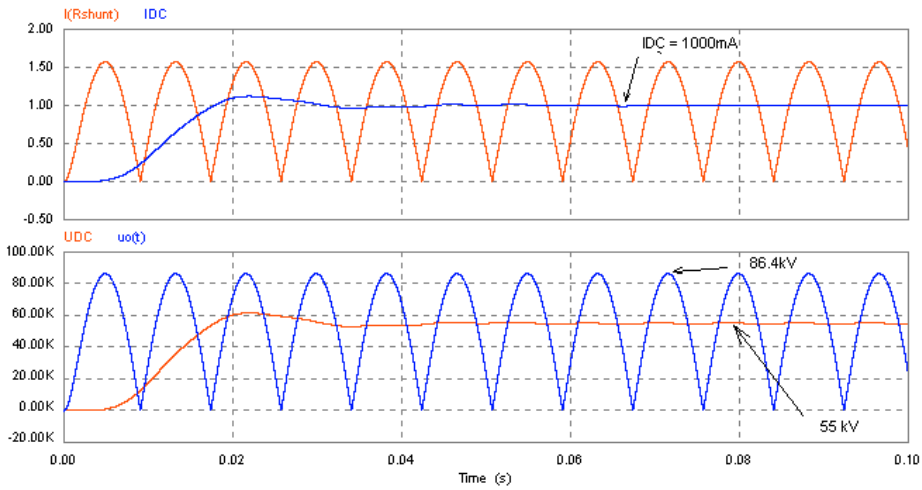
But the main differences are normally found in the rated output voltage, as it will be explained in the following.

3.1. The American way

The rated output voltage is normally expressed as the mean voltage obtained when the T/R set is loaded with a pure resistance giving an output mean current equal to the rated output current $\mathbf{I_{O\text{-}mean}}$.
In Fig. 2 is shown an example for a 1000mA/55kV T/R set connected to a 440V/60Hz mains. It is supposed that the short-circuit voltage of the set is 33%. A number of simulation programs exist on the market. In this paper the program POWERSIM has been used. For the sake of simplicity in all simulations it has been adopted that the ESP voltage is positive.



(a)



(b)

Fig. 2 Example of a T/R set loaded wit a pure resistive load

The waveform of the output voltage and output current are as shown in Fig. 2.b. Because of the voltage drop on the current limiting reactor the loaded secondary RMS voltage $U_{S\text{-}RMS}$ is 86.4kV; i.e. 7% lower than the secondary RMS voltage delivered by the HV transformer at no-load ($U_{So\text{-}RMS}$ = $\sqrt{2} \cdot 440 \cdot 148$ = 92.1kV). Because the form factor for this voltage waveform is 1.11, the output mean voltage $U_{o\text{-}mean}$ as a function of $U_{So\text{-}RMS}$ can be expressed as:

$$\mathbf{U}_{o\text{-}mean} = \mathbf{U}_{S\text{-}RMS}/1.11 = \mathbf{U}_{So\text{-}RMS}/(1.07 \cdot 1.11) = \mathbf{U}_{So\text{-}RMS}/1.189 \qquad (6)$$

Another issue can sometimes be the ESP current form factor, which in some cases can be only 1.2. This means that when the T/R energizes an ESP load giving a form factor around 1.4, the primary current should increase correspondingly, causing tripping of the circuit breaker on the primary side. This may be relevant in case of ESP fields lying at the outlet end of the ESP.

3.2. The European way

In spite that in the past the rated voltage has been unclear, the present tendency is to use the peak no-load voltage ($\mathbf{U}_{o\text{-}peak}$). But other forms can be found. For instance in the past some manufacturers used the secondary RMS no-load voltage ($\mathbf{U}_{So\text{-}RMS}$). Another manufacturer used e.g. the loaded peak voltage as rated voltage.

3.3. Equivalence between the American and the European rated voltage

By using eq. (3) and (7) it can be written:

$$\mathbf{U}_{o\text{-}mean} = \mathbf{U}_{So\text{-}RMS}/1.189 = \mathbf{U}_{o\text{-}peak}/(1.189\cdot\sqrt{2}) = u_{o\text{-}peak}/\ 1.681$$

$$\mathbf{U}_{o\text{-}peak} = 1.681 \cdot \mathbf{U}_{o\text{-}mean} \quad (8)$$

In other words, eq. (8) tells us that the conversion factor between the American and the European output rated voltage is 1.681.

Example: A 55kV T/R manufactured in USA will be equivalent to a 1.681·55 = 92 kV in Europe, where the most accepted rating is the peak no-load voltage.

4. Probable reason for not using the peak no-load value as rated voltage

The author thinks that the root of the problem maybe resides in the fact that the peak no-load voltage can be difficult to measure in practice. The reason is that this voltage could be dependent on the type of voltage divider used by the manufacturer, and also on the firing angle used. The worst angle is 90° and this value can cause a considerable overvoltage (almost 100%) as illustrated in Fig. 3.b.

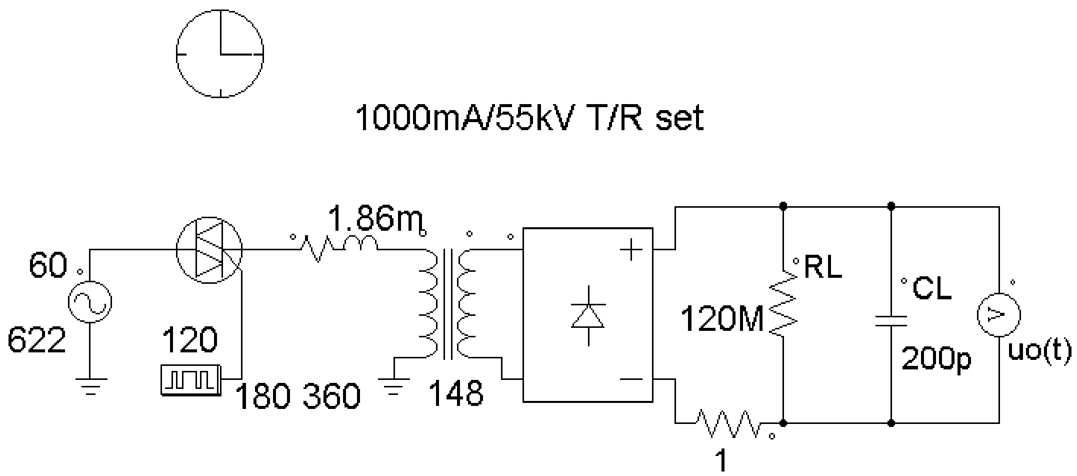


Fig. 3.a. Circuit used in the PowerSim simulation

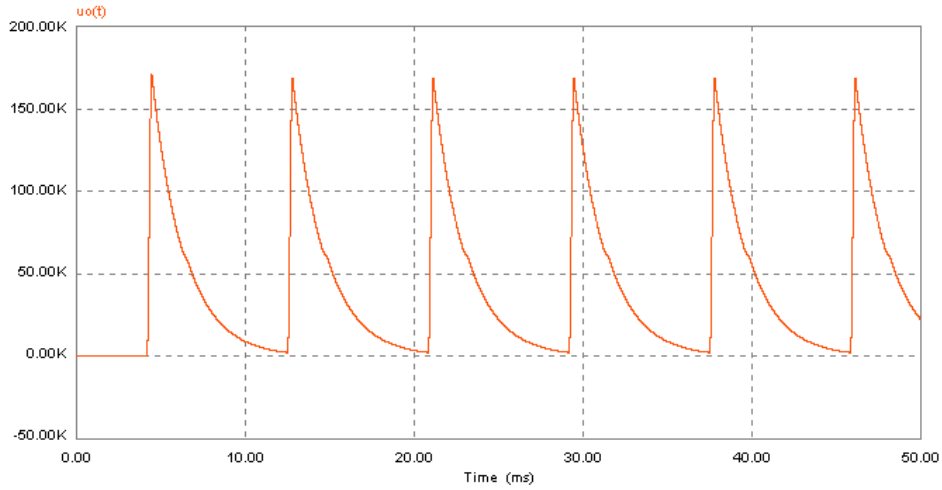
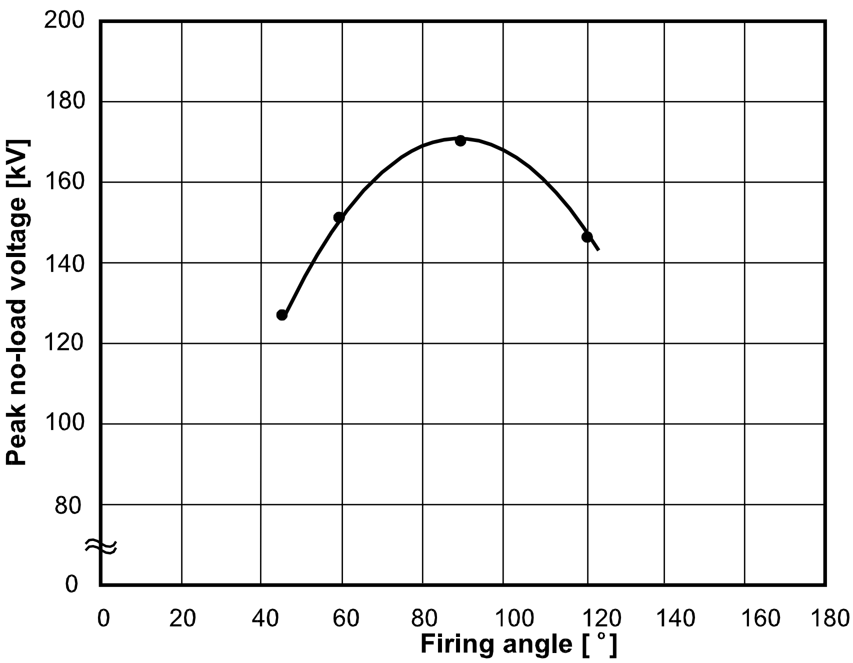


Fig. 3.b Output voltage waveform at no-load with 90º firing angle

As seen in Fig. 3.a, the T/R is supposed to be loaded only by the top resistance of the voltage divider (120MΩ) and capacitances from the HV diode rectifier and HV bushing (200pF). It appears that the peak output voltage can reach 171 kV, which is considerably higher than the rated peak value of 92 kV.

Therefore, the author advocates for the use of the transformation or turns ratio as the best way to express the voltage capabilities of the T/R set when loaded with an ESP load. This will avoid a lot of confusion and time wasting which sometimes happens when evaluating the performance of the T/R set during commissioning, troubleshooting and especially in case of retrofit projects.



In case of a no-load test is carried out, e.g. when the T/R is tripped by an undervoltage condition, it is important that the firing angle used in this test is the correct one in order to avoid overvoltage, which may be dangerous for the T/R set.

In Fig. 4 is shown the attainable peak value as a function of the firing angle. It is seen that a firing angle of 90º gives the highest peak voltage. Moreover, in the range shown, the peak voltage is higher than the rated voltage, so care should be taken when performing such a no-load test.

Fig. 4 Attainable peak no-load voltage as a function of firing angle

In the following section it will be illustrated by an example the way the voltage capability of a T/R set can be determined by computer simulation and by using the relevant data that should always be included on the rating plate.

5. Attainable mean voltage with an ESP load

This will be illustrated by an example where the T/R is described by:

$\mathbf{U}_{P\text{-}RMS}$= 440 Vrms;	**n** = 145;	$\mathbf{e}_{SC}$ = 33%;
$\mathbf{I}_{o\text{-}mean}$ = 1000 mA;	$\mathbf{I}_{P\text{-}RMS}$ = 203 A;	**f** = 50Hz

With this data it is possible to determine all relevant values. For instance:

The peak no-load rated voltage is: $U_{o\text{-}peak} = \sqrt{2} \cdot n \cdot U_{P\text{-}RMS} = 1{,}41 \cdot 145 \cdot 440 = 90$ kV

The current form factor at rated current is: $$FF = \frac{I_{P-RMS}}{n \cdot I_{o-mean}} = \frac{203}{145 \cdot 1} = 1.4$$

The shortcircuit inductance is: $$L_S = \frac{U_{P-RMS} \cdot e_{SC}}{I_{P-RMS} \cdot \omega} = \frac{440 \cdot 0.33}{203 \cdot 2 \cdot \pi \cdot 50} = 2.28\ \text{mH}$$

The T/R set used in this example is shown in Fig. 5.

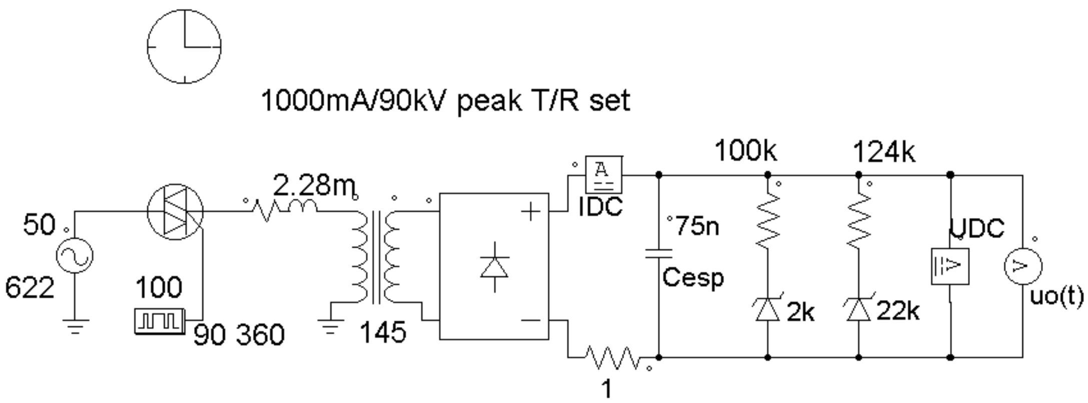
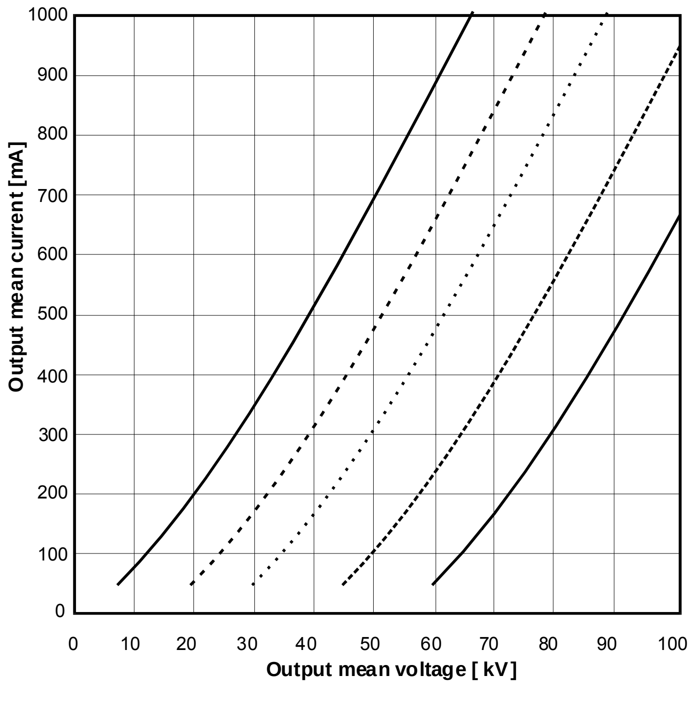


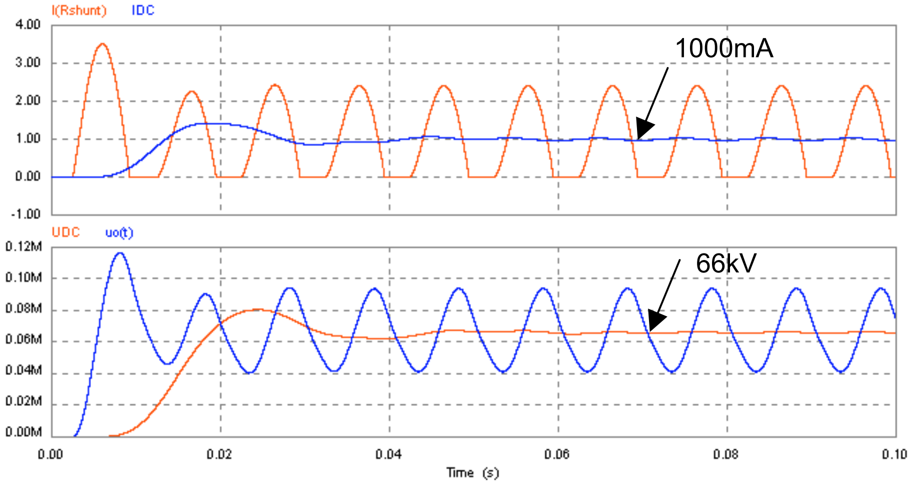
Fig. 5 Circuit used in determining the output voltage and current with an ESP-load



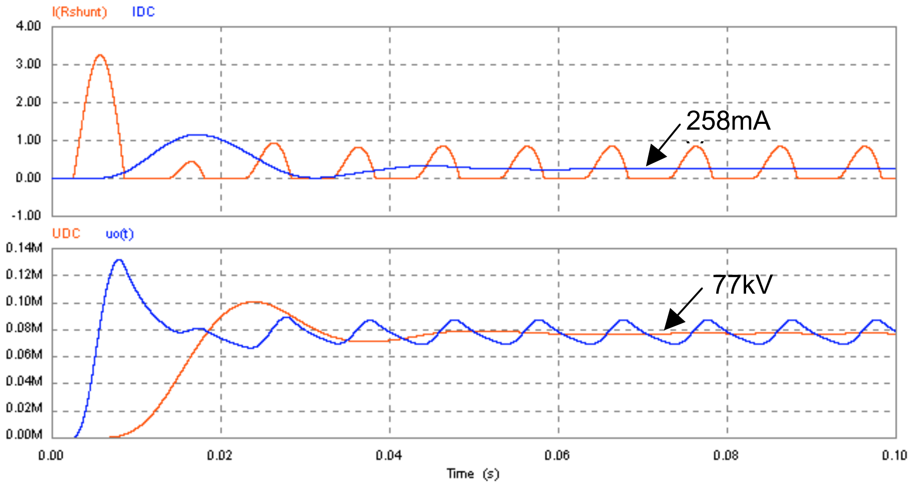
It is supposed that the T/R set energizes 2500m^2 of collecting plates and the capacitance of this field is 75 nF (30pF/ m^2). The corona load is represented by a 2 stage piecewise linear circuit with zener diodes and resistors. The corresponding current-voltage characteristic is shown in Fig. 6. In order to increase the counter-emf (**e**lectro**m**otive **f**orce) represented by the load, the CVC is displaced stepwise to the right toward higher voltage values as seen in Fig. 6 (outmost left). The thyristors are fired as early as possible, without any other limitation than the existing counter-emf.

The results (IDC and UDC) for the loads (CVC's) giving the lowest and highest counter-emf are shown in Fig. 7.a and 7.b respectively.

Fig. 6 CVC's used in the output voltage determination



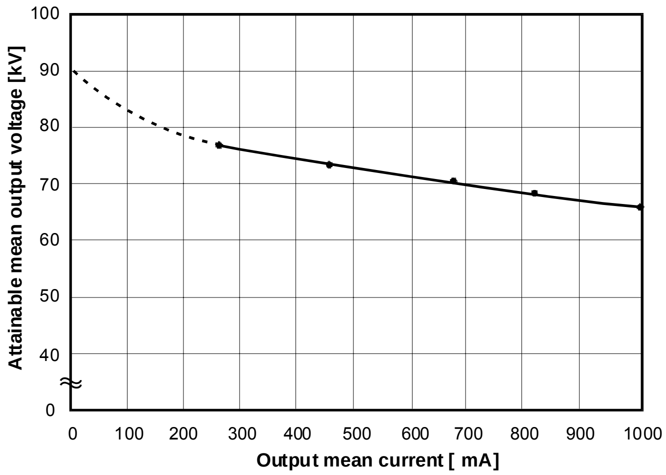
(a)



(b)

Fig. 7 Mean output current and voltage with 2 different ESP load an early firing

It is seen that the output mean voltage, with this load span, can vary between 66 and 77kV. The corresponding values for the mean current are 1000 mA and 258 mA, respectively. Other points between these limits have been determined using the CVC's shown in Fig. 6 with dotted lines. The results are plotted in Fig. 8.



In this example it is seen that the max. mean output voltage at rated current is 66 kV. If the ESP load (CVC) demands higher voltages, the current delivered by the T/R set becomes smaller and smaller.

This method can be used to determine the T/R set voltage capabilities, e.g. with other short-circuit voltages or other rated voltages.

Fig. 8 Mean output current and voltage obtained with different ESP-loads

6. Conclusion

It has been shown that by knowing few important values like:

- Rated primary voltage (U_{P-RMS})
- Rated primary current (I_{P-RMS})
- Transformation ratio (n)
- Short-circuit voltage (e_{SC})
- Output mean current (I_{O-mean})

the T/R set is completely defined and other values can be determined by simple calculations. In order to determine the output voltage capabilities for different short-circuit voltages (c) and ESP-loads, a computer simulation can be performed.

The transformation ratio of the high voltage transformer (n) and the short-circuit voltage (e_{SC}) is normally not indicated on the rating plate. Sometimes the transformation ratio can be derived from e.g. the rated no-load peak voltage or from the form factor, when these are indicated, by using eq. (2) and (3).

Nevertheless, the shortcircuit voltage is normally not indicated on the rating plate, making difficult the assessment of the performance of a T/R set for a particular application.

It has been demonstrated that the T/R set operation under different loads can be determined in an easy way by computer simulation. In particular it is important to note that a no-load test has to be carried out with precaution by the service personnel in order to avoid dangerous overvoltages. In this case it is important that the control unit includes the facilities to perform this test in a correct manner and that its instruction manuals consider this test in particular.

Finally, it is the author's hope that this paper can contribute to a better understanding of the T/R set operation between ESP-manufacturers and end-users, so that the T/R set manufacturers will meet the same demands from their clients. This will lead to a more uniform way of marking the T/R sets, and by doing so, mistakes and time wasting will be avoided in the future when relevant data for the T/R set will be required for solving a particular problem.