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THE GENERATION OF LIGHTNING AND SWITCHING IMPULSE VOLTAGES IN THE UHV REGION WITH AN IMPROVED MARX CIRCUIT

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Abstract - This paper concerns the trigger performance of Marx circuits and shows the essential features of an improved circuit. It is studied how the introduction of parallel spark gaps PF and firing capacitors C_z in a multi-stage impulse generator can improve the trigger performance. Other advantages of the new circuit will also be discussed.

INTRODUCTION

Impulse generators for high voltage testing has been built up to now almost exclusively in the well known Marx circuit. The basic principle of this circuit is the rapid series connection of charged capacitors whereby spark gaps are used to make the series switching.

One of the main problems of Marx circuits with output voltages of some million volts is the reliability of the series switches, e.g. the spark gaps. Until up to about 15 years ago when Broadbent /9/ made his proposal to trigger all stages, it was almost exclusively only the first stage of the generator which was triggered. The remaining stages were switched successively in series as a result of overvoltages originating from the voltage breakdown at the first spark gap. The level of the overvoltages on these spark gaps not yet fired was thus decisive for the successful series connection of all capacitors.

The parameters which influence the overvoltages are in the main, the stray capacitance (earth and interstage capacitance) - which are given fixed to the requirements of the construction - and the front and tail resistors /1/, /2/, /3/. In other words, some parts of the main structure of the Marx circuit have a twofold function. One function is to generate and form the output voltage e.g. the lightning or switching impulse up to some million volts. The other function is to generate internal overvoltages to fire the spark gaps which have to make the series switching of the charged capacitors. Because these overvoltages are part of the natural behaviour of the given Marx structure, they are often called natural overvoltages.

TRANSACTIONS PAPER

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In practice in two very important cases the resistance values work unfavourably in respect of the natural overvoltages on the spark gaps which are not yet firing:

- If the generation of switching impulse voltages is required with front times of several 100 μs using front resistors built into the individual generator stages (internal front resistors).

- If it is required to attain tail times of 50 μs for the generation of standard lightning impulse voltages in impulse generators of high stage energy, that is, of high capacitance per stage.

In the first case, the high front resistors between the individual stages of the generator and, in the second case, the low ohmic tail resistors work at every stage in a strongly damping manner on the spark gaps not yet firing and, in so doing, endanger the mechanism of the series switching of the charged capacitors.

For impulse generators with high energy in the stages (from about 10 kJ per 200 kV stage) and for generators with the generating facility for high switching impulse voltages, this has led to the development of new trigger circuits, in which in principle two remedies are current practice:

- Attempt is made to attain the firing of the spark gaps even without natural overvoltages or

- It is attempted by means of corresponding circuit arrangements to increase the overvoltages and thus it is possible to continue to use the untriggered sphere-gap as a switching unit.

In the following a solution is reported which leads to the successful series switching of all capacitors with natural overvoltages.

Requirements for a Switching System

The following requirements among others, are necessary for a series switching system to connect the charged capacitors in series for industrial testing with the standard lightning and switching impulse voltages :

- A mechanism which operates independently of the charging voltage in the range from 5 % to 100 % of the charging voltage.

- A mechanism which gives negligible scattering of the switching process ($\leq$ 50 ns) even with changing charging voltages! (from 5 % to 100 % of the charging voltage).

- A release working range which is large enough to facilitate the triggered firing sufficiently far below the static breakdown voltages of the spark gaps.

- A switching spark gap with extremely long maintenance-free life, i.e. reduced erosion.

- A switching spark gap with a low arc voltage drop in the full operating area from 5 % to 100 % of the charging voltage to prevent noticeable non-linearities in the test circuit.

- A switching spark gap with reduced scattering of the static breakdown voltage.

- A switching spark gap which does not become extinguished even at low currents, that is, at high series and tail resistors.

These requirements are dictated, , above all, by the test specifications for the testing of transformers with tightning impulse voltages. For research on gas discharges or for the generation of switching impulse voltages a part of these requirements can be disregarded.

An improved Circuit for the reliable Series Switching of a Marx Circuit with natural Overvoltages

In order to fulfil the stated requirements (apart from the encapsulation of the spark gaps which is always necessary to prevent erratic firings because of ambient influences/4/), a circuit variation is being developed which leads, furthermore, to the series switching of the capacitors via sphere-gaps and facilitates firing of the sphere-gaps (with the exception of the first) by means of the natural overvoltages. This solution was chosen, in the first place, because the linearity of the switching spark gap, the spark erosion (maintenance-free life) and the extinction of a spark gap can best be controlled with a sinele spark gap. Secondly linearity of the output voltage from the charging voltage can only be achieved through release with natural overvoltages.

These considerations are confirmed from the ten years' experience with impulse generators with up to 30 spark gaps. Thus it has been shown that 30 arc voltage drops can be tolerated correspondingly, without, for example, getting into difficulty with very sensitive error detection in transformer tests. In contrast to this an increase in the number of sparks of an order of ten, for example, by the introduction of multiple spark gaps as switching unit for series connection, together with a high trigger voltage (which ensures successful series switching, even at 10 % of the static breakdown-voltages) leads apparently to considerable non-linearity /8/.

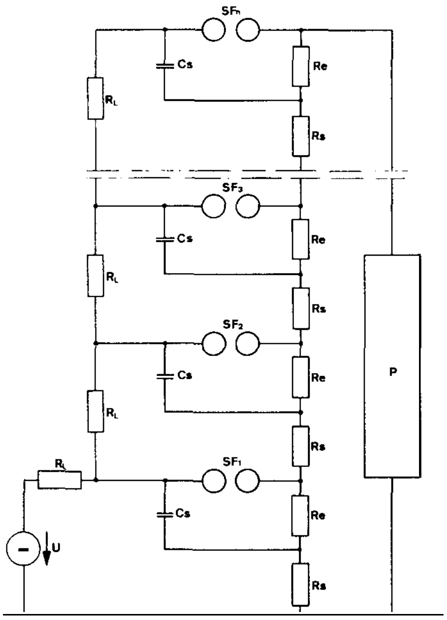

Fig.1.Familiar Marx Circuit

Fig.1 shows the familiar Marx circuit, which at high stage energies (low tail resistor R_e), or in the generation of switching impulse voltages (high series damping resistor R_s), leads to difficulties in the triggered firing of multi-stage generators (number of stages $n > 10$). Apart from being able to avoid these difficulties by the new circuit further introduced below, they could also be avoided for not too high impulse voltages, by external front resistors (for the switching impulse voltage) and by external tail resistors (for the lightning impulse voltage). External resistors, however, are no longer applicable in very high voltages in the UHV region - on account of the voltage stability of these resistors. Moreover, they reduce the flexibility of a generator and enlarge the test circuit. For this reason, impulse generators for total charging voltages above 4 MV are, in practice, built only with internal front and tail resistors.

As an example, for a 24 stage impulse generator with a total energy capacity of 480 kJ which is designed as *a* standard Marx circuit as in Fig.1, gives a working range of about 12 % in the complete series circuit in the generation of a lightning impulse voltage of 1.2/50 µs. That is to show that the normal series switching is only possible up to 12 % below the static breakdown voltage of the spark gaps, which is very low. Working ranges of at least 20 % are worth the effort in order to obtain reliable adjustment of the spark gaps with negligible rate of erratic firing under all ambient conditions. In the parallel circuit with a number of stages, the working range of the above mentioned generator is still a lot less than 12 %, as the tail resistor is further reduced by the parallel circuit of the stages.

In the same way the working range in the standard circuit (Fig.1) is narrowed when switching impulse voltages with front resistors of a few kOhm are to be generated. For example, the front resistors in a 10 stages impulse generator with a small capacitive load can be a few kOhm in order to generate the standard impulse voltage 250/2500 μs. In this case (10 stage impulse generator, $R_{s/stage}$ = 5000 Ohm) the working range becomes about 8 % for the generation of the switching impulse voltage 250/2500 with a circuit corresponding to Fig.1.

These two examples show, that the working range in the standard Marx circuit can become so small that a reliable firing is no longer guaranteed. These facts have led to the development of the improved circuit, in which two courses of action are necessary in order to obtain a good working range at all possible combinations of the resistors. Fig.2 shows the circuit diagram for the new circuit. To the familiar circuit, as Fig.1, is added a firing capacitor C_z and a parallel branch to the tail resistor R_{e1} in each stage.The parallel branch to the tail resistor R_{e1} consists of a spark gap PF and a resistor R_{e2}. R_{e1} is of high ohmic value and so designed that the impulse capacitor C_S discharges through this alone in a tail time of about 2500 μs. On the other hand R_{e2} is so low in ohmic value that the impulse capacitor C_S can discharge itself through this resistance in as short a time as 50 μs.

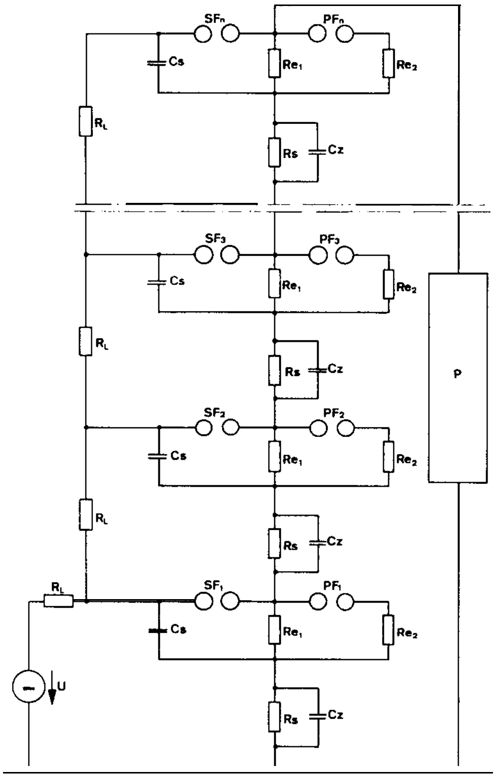

Fig.2.Improved Marx Circuit

We will explain firstly the method of operation of the parallel branch to the tail resistor R_{e1}, consisting of the spark gap PF and the resistor R_{e2}. At the beginning of the series switching operation all the low ohmic resistors R_{e2} are disconnected by the spark gap PF. Thus good conditions exist for a reliable change-over to the series connection for the "normal" Marx circuit and this is because the high ohmic resistors R_{e1} alone are effective. Only afterwards when the spark gap SF has fired in a certain stage and thus has carried out its function - does the spark gap PF of the same stage fire, in order to switch into the circuit the low ohmic resistor R_{e2}. The spark gap PF is so adjusted that it does not fire, before the firing of SF of the next stage through a transient voltage across R_{e1}, but fires reliably as soon as a higher voltage arises at R_{e1} after the firing of SF.

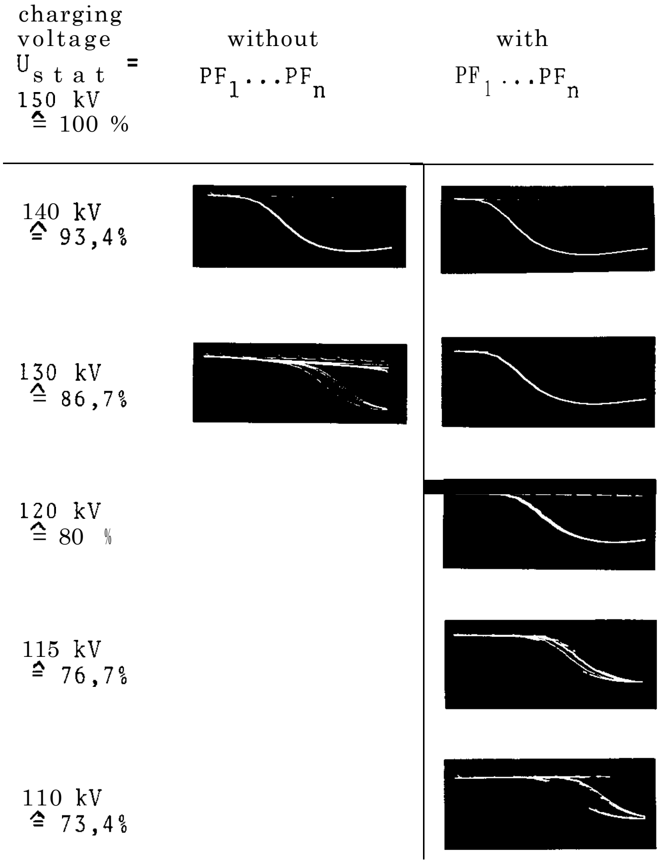

Fig.3.Trigger range of a Marx impulse generator for negative lightning impulse voltages with and without parallel sphere-gaps (time scale: 0.25 μs/unit) .

Test Generator: 4.8 NV-multi-stage generator, 480 kWs, 24 stages.

This two-step discharge circuit improves the working range in the generation of a lightning impulse voltage 1.2/50 μs from 12 % to 28 % in the above mentioned example (24 stage impulse generator) /5/, /6/. As Fig. 3 shows, the scatter in the firing is less than ± 50 ns in a working range of 20 %. In each oscillogram in Fig.3 ten voltage impulses are superimposed one over another. The whole range of the charging voltage is set automatically by means of an additional gap adjustment of the sphere-gap by a pre-selected value of the charging voltage. The two stage discharge circuit also offers the additional advantage that by means of adjustment of the parallel spark gap, the tail time can be switched over from 50 μs to 2500 μs within a short time - without the resistances having to be changed in their position.

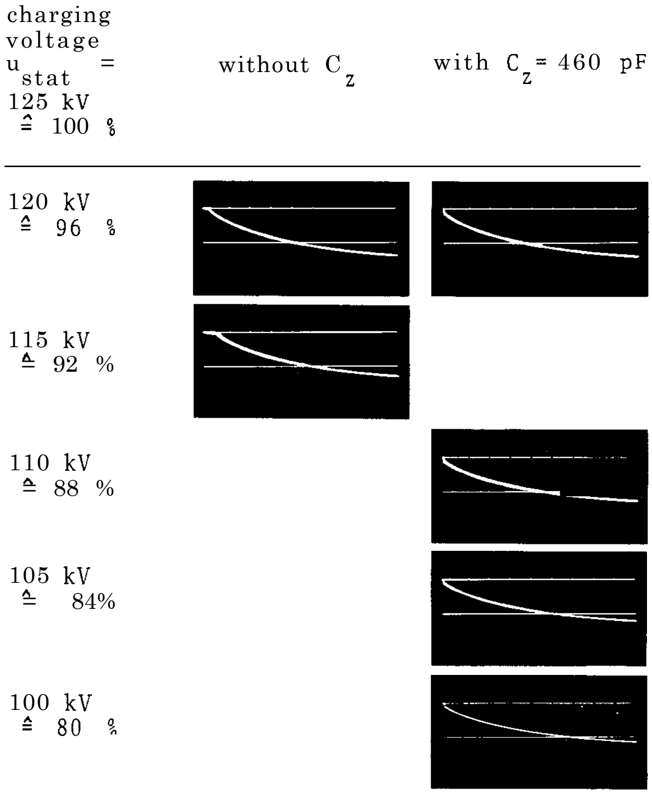

Fig.4. Trigger range of a Marx impulse generator for negative switching impulse voltages with and without firing capacitor (time scale: 10 μs/unit)

Test Generator: 2 W-multi-stage generator, 150 kWs, 10 stages.

In the generation of switching impulse voltages the parallel spark gap is opened up. A high front resistor of several kOhm damps the high frequency overvoltages arising, so that no transient natural overvoltages arise in the spark gaps not yet firing. The transient high frequency overvoltages can be transmitted to the following spark gap through a low impedance for high frequencies. This is done by a firing capacitor C_z of some hundred pF parallel to the front resistor /7/.

Fig.4 shows the increase in the working range achieved, for a 10 stage impulse generator with a front resistor of 5000 Ohm per stage through the integration of a firing capacitor. Without the firing capacitor the working range amounted to 8 %. With the firing capacitor it is 24 %, so that in a working range of about 20 % negligible scatter (< 50 ns) arises.

In the generation of lightning impulse voltages no disadvantageous effects of the firing capacitor on the working range and on the shape of the output voltage could be established.

A properly designed firing capacitor had no detrimental effect even in the shape of chopped lightning impulse voltages, so that the firing capacitor can be fixed into the impulse generator /7/.

With the help of firing capacitors even it was possible to obtain a working range as with lightning impulse voltages with front resistors of 15 kOhm per stage. That is to say, it is possible to generate front times of more than 1000 μs, even with a sufficiently large working range with this improved circuit.

CONCLUSION

With the help of parallel spark gaps PF and firing capacitors C_z an improved Marx circuit is possible, which produces a sufficiently wide working range of the switching spark gaps with natural overvoltages, at all resistance values arising in practice for the tail resistor R_e and for the front resistor R_s. Furthermore, the simple sphere-gaps can be installed as a switching unit for the generation of high unipolar impulses. The advantage of the presented circuit lies in the linearity of all units employed on the one hand and, on the other, in the robust, simple and reliable switching spark gap.

REFERENCES

/1/ A. Rodewald, “Ausgleichsvorgange in der Marxschen Vervielfachungsschaltung nach der Ziindung der ersten Schaltfunkenstrekke,” Bull.SEV 60(1969), S.37-44.

/2/ A. Rodewald, “Die Ziindwahrscheinlichkeit der Schaltfunkenstrecken in der Marxschen Vervielfachungsschaltung,” Bull.SEV 60 (1969), S.857-863.

/3/ F. Heilbronner, "Firing and Voltage Shape of Multistage Impulse Generators," Trans. IEEE on Pow.App. and Syst. Vol.90(1971),5 pp.2233-2246.

/4/ A. Rodewald, "Zur präzisen Auslösung von Stossgeneratoren bei einer vorgewählten Ladespannung," Bull.SEV 59(1968), S.947-952.

/5/ A. Rodewald, "Ueber eine Marxsche Vervielfachungsschaltung mit Hilfsfunkenstrecken zur Verbreiterung des Auslösebereiches," ETZ-A 92(1971), S.56-57.

/6/ K. Feser, "Gedanken zur Stossspannungserzeugung und Prüftechnik für die Entwicklung von UHV-Systemen," Bull.SEV (will be published soon).

/7/ K. Feser, "Erweiterung des Auslösebereiches von vielstufigen Stossgeneratoren für die Erzeugung von Schaltstosspannungen," ETZ-A 94(1973), S.171-174.

/8/ M.J. Bishop, M.F. Simon, "The Impulse Generators at Les Renardières," Trans.IEEE on Pow.App. and Syst. Vol.91(1972), 6, pp. 2366-2376.

/9/ T.E. Broadbent, 'New high voltage multistage impulse generator circuit," Journal of Scientific Instruments 37(1960), pp.231-236.

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Discussion

N. Hyltèn-Cavallius (Hydro-Québec Institute of Research, Varennes, P.Q., Canada): The authors demonstrate how the triggering range of an impulse generator can be improved by the use of an additional gap and capacitor circuit.

However, there is an additional problem related to the gaps of an impulse generator. Sometimes small disturbances have been found on the impulses which can be explained by the assumption of too early extinguishing of the gaps. These disturbances have practical importance only in the case of transformer testing where they can be mistaken for transformer failures.

Have the authors any information on this phenomenon with their triggering arrangement such as some oscillograms with relatively long time sweep?

Manuscript received July 19, 1973

G. Leroy, G. Gallet, and M.F. Simon (U.H.V. Laboratory "Les Renardières", France): The authors have to be congratulated for the improvements that they have promoted on the conventional sphere gaps firing system which was previously not well adapted for switching and lightning impulses generation in the UHV range. For the sake of clarity we would like the authors to comment the following points:

1. Switching scatter

Page 1 is stated that the scatter in switching process should be below 50 ns from 5% to 100% of the charging voltage. We understood from fig. 3 that this characteristic is obtained with authors' generator by adapting the gap spacing in function of the charging voltage and that for one gap setting the scatter remains below 50 ns only during 15% of the total charging voltage.

We would like to say here that the measurement of 50 ns scatter is not an easy one and further that we don't understand quite well how with a 250 ns per square (see fig. 3) one can detect with precision 2/10 of it.

Figures 1 and 2 show the results obtained in Les Renardières on a 6 MV generator triggered by polytrons (10 superimposed lighting impulses). The sweep of the oscilloscope was 100 ns/square, and in [1] was only given the upper limit of the measurements totally reproduced on figure 2. As one can see the jitter from 10% to 100% of the charging voltage is practically near or below 50 ns (one can withdraw from the width of the 10 superimposed traces the width of a single trace but this has not been done for the evaluation presented fig. 2). The advantage of the polytron system is that it is completely independant from the reliability of the mechanical arrangement necessary with conventional sphere gaps for gap spacing adjustments.

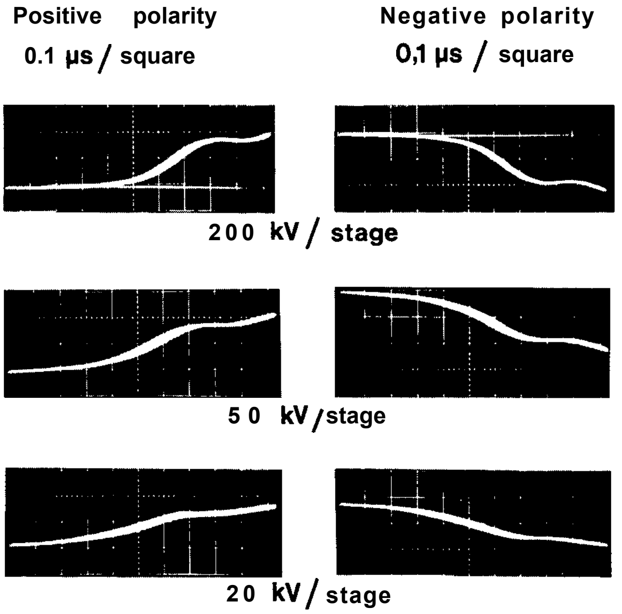

Fig. 1 Jitter on a 6 MV impulse generator operated with polytron gaps under lightning impulse.

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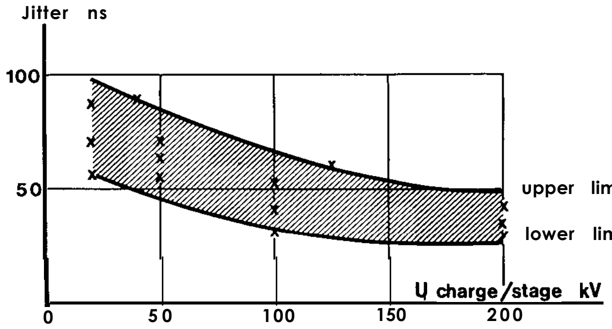


Fig. 2 Variation of the jitter on a 6 MV impulse generator operated with polytron gaps under lightning impulse as a function of the charging voltage.

2. Generator efficiency

2.1 Absolute efficiency

The authors state that their generator is able to generate front times of more than 1,000 µs. Could they be more precise and give some figures experienced with the efficiency measured?

With the 6 MV generator installed in Les Renardières we have produced impulse shapes up to 2,200/7,000 µs and 2,200/12,000 µs with an efficiency of respectively 40% and 70%. Nevertheless after 2.5 MV in switching impulse of positive polarity the efficiency is deeply affected by heavy predischarges occuring either in the circuit or on the top electrode of generator [1] and [2].

Have the authors experienced the same with their 4.8 MV generator? Have they developed a top electrode and if so with what maximum gradient?

2.2 Relative efficiency

It is true that the voltage drop along a polytron is greater than the one of a conventional sphere gap (provided it is correctly adjusted) but the statement presented by the authors saying that this characteristic leads to considerable non-linearity is false.

In figure 5 of [1] we measured on our 6 MV generator fired by polytrons a maximum non-linearity of 4% from 10% to 40% of the total charging voltage. But from 40% to 100% of the total charging voltage the non-linearity is below 0.5% (accuracy in the measurement).

This means that it is always possible to operate the generator in a working range where no non-linearity is detectable. But further non-linearity observed being perfectly reproducible can be taken into account by an adequate piloting of the generator either manually of automatically. Up to now this has never been for us a limiting factor. One can judge it by considering the two kinds of experiments which are normally required namely: measurements of flashover characteristics (up and down or conventional testing procedure) and withstand tests. During the measurement of flashover characteristics, the operating range being about 30% (± 3 σ) of the charging voltage, the error committed is below 1% (when no correction is made) which is within the total measuring error.

During withstand tests the correction has to be made but from 25% to 100% of the charging voltage it remains below 1.5%. This correction will in fact be realized in Les Renardières when a computer will be interfaced with the existing equipment complemented by Analog Digital transient recorders.

REFERENCES

[1] "The Impulse Generators in Les Renardières", by M.J. Bishop and M.F. Simon – PAS vol. 91 number 6, pp. 2366 to 2376.

[2] "Contribution to a Better Understanding of Impulse Voltage Measuring Systems", by M.F. Simon and G. Leroy – PAS vol. 91 number 2, pp. 478 to 484.

M.J. Bishop (Ferranti Limited, Lancashire, England): Whilst the authors' solution to the difficulties they have encountered in obtaining satisfactory triggering because of the high energy of their impulse generator is no doubt extremely effective, I was surprised to learn how poor was the triggering performance prior to the modification. I can only assume that this was due to the single stack form of construction which they have adopted.

Manuscript received August 2, 1973.

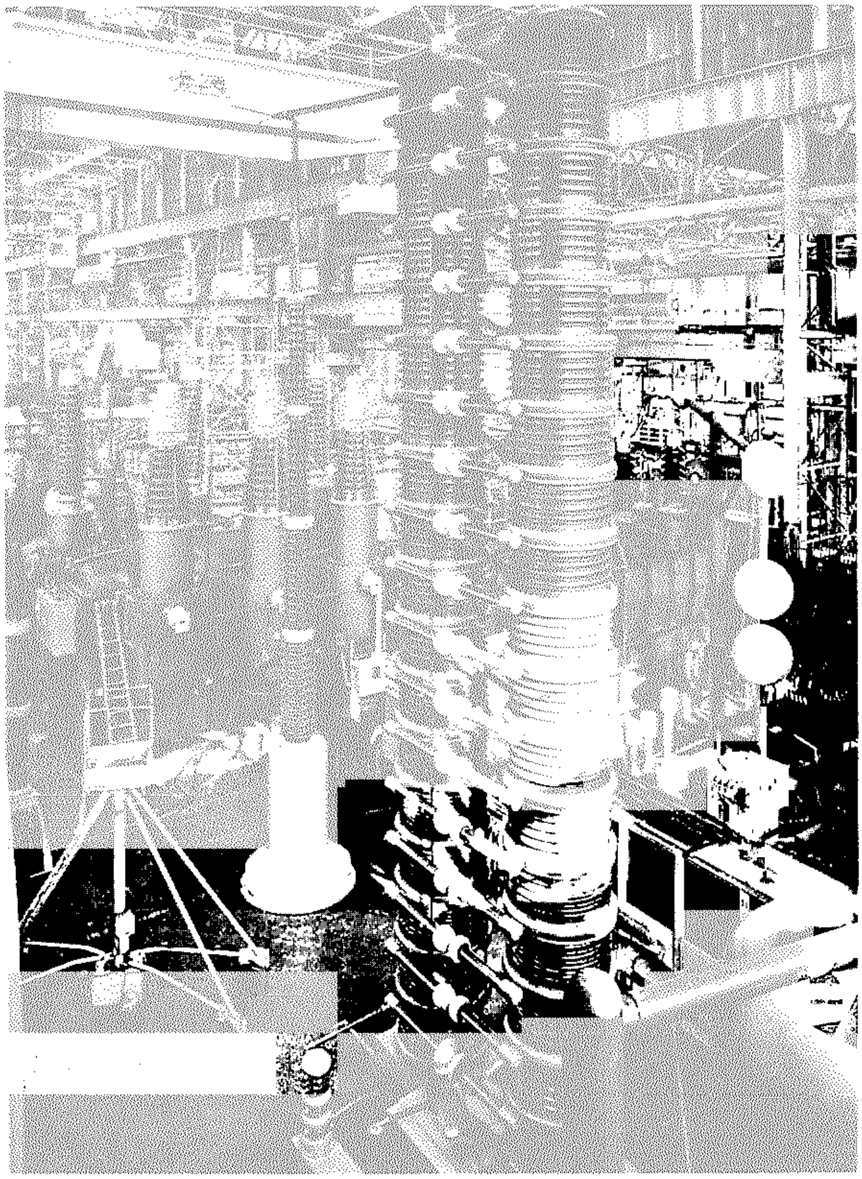
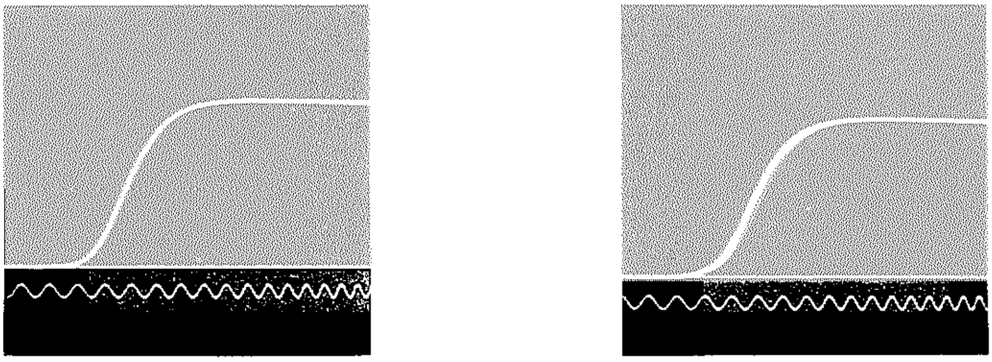


Fig. 1



(a)
10 impulses @ Vc = 100kV (0.8 Vs)

(b)
10 impulses @ Vc = 95kV (0.76 Vs)

Sphere dia. = 250mm Spacing (all gaps) 45mm
Vs = 125kV Time calibration : 5 MHz

With a generator constructed in two stacks (Fig. 1), a much better trigger performance is obtained as is evidenced by the oscillograms of Fig. 2. The generator is also of 200kV/Stage, with a slightly higher energy content than that of the authors at 12.8kJ/Stage.

The oscillograms show that with the spark-gaps set for a nominal sparkover voltage Vs = 125kV, and with internal wavefront and wavetail resistors of 25 ohms and 100 ohms respectively, a scatter less than 50 n sec is achieved at a charging voltage Vc = 0.8Vs. Although the scatter is slightly above 50 n sec at Vc = 0.76 Vs, the generator does not fail to trigger.

These results do not seem to be significantly inferior to those of the authors, although they were achieved without the added complication of a second set of adjustable spark-gaps.

The statement made by the authors that an operating range down to 5% of the maximum charging voltage is necessary seems to me to require some justification. Apart from the fact that I know of no case where the range of voltage in a single test exceeds 5 : 1, the choice of 5% will require an accuracy in the gap setting of the order of 1/3mm, if variations in setting are not to exceed about 10% of the nominal gap dimension. Can the authors supply any information upon the accuracy with which the gaps can be set on their 24 stage generator.

A number of comments have been made by the authors concerning the disadvantages of triggered multiple gaps (1). I feel that I should point out that one of the principal reasons for the introduction of this alternative solution to the problem was because of the relatively poor stability of the conventional gaps.

We have found that even if the gaps of agenerator such as that of Fig. 1 are enclosed and supplied with filtered air of controlled humidity, the incidence of self-triggering is unacceptably high for present day testing needs.

Thus with a generator having 10-20 stages being operated with Vc in the region 150-200kV, the number of charges which result in self-triggering can be as high as 5-10% under certain circumstances, even though Vc < 0.8Vs.

By reducing the volume of air under stress by a factor of several hundred and obtaining a ratio Vs/Vc much greater than is practicable with conventional gaps, the probability of self-triggering with the multiple gap (polytrigatron) can be reduced to an acceptable level.

Provided that a suitable material such as tungsten-copper is used for the electrodes the rate of erosion is sufficiently low to permit maintenance to be carried out in most cases on an annual basis.

Since no difficulties are experienced in triggering under any circumstances including series-parallel connection, and the system involves no moving parts, the variation in efficiency which occurs (2% over the range of charging voltage from 40-200kV) seems a very small price to pay.

REFERENCES

[1] "A New Method of Triggering for High Voltage Impulse Generators," Ferranti Limited, Chadderton, England.

A. Rodewald and K. Fesser: The authors wish to thank the several discussors for their comments and interesting questions. We think it is of special interest that the experts of other generator systems have presented some additional informations of their design and especially the ideas leading to their solution.

As Mr. Hyltén-Cavallius has pointed out the linerarity of the output voltage versus the charging voltage is very important for transformer testing.

Linearity means:

a) The amplitude of the generated impulse voltage depends linear on the charging voltage or at least in a predictable manner.

b) The shape of the generated impulse voltage may not change with the charging voltage. This second kind of linearity is very important, because in case of non-linearity it is impossible to distinguish between non-linear effects coming from the generator and failures appearing in the test object.

The question of Mr. Hyltbn-Cavallius belongs to this second field of non-linearity, because an extinguishing of one gap can be taken as a transformer failure.

During the acceptance tests of the 4,8 MV-impulse generator, where parallel gaps were included, this problem was studied very closely, but we could not measure any influence of this parallel spark gap upon the impulse voltage one. The measurements were done in series connection of all stages and also in different series/parallel connections. Fig. 1 shows an oscillogram of the impulse shape with a longer time sweep. No discontinuity in the tail can be registrated.

Manuscript received October 15. 1973.

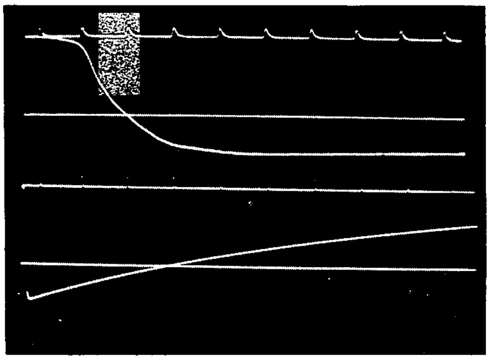


Fig. 1 Lightning impulse voltage 1,2/50
polarity: negative
crest value: 4100 kV
upper trace: 0,5 μs/unit
lower trace: 10 μs/unit

This result can be explained because the distance of this parallel gap is settled automatically to half the distance of the main gap and the arc voltage drop across a single gap is only some 10 V.

The authors thank Mr. Leroy, Mr. Gallet and Mr. Simon for their additional informations concerning the performance of their generator at Renardières, especially the switching behaviour of the polytrigatron. The whole trigger range of 5% to 100% of the charging voltage is in our case obtained by adapting the gap spacing in function of the charging voltage. This is done automatically by a control unit in such a way that over the whole trigger range of 5% to 100% charging voltage the scatter is below 50 ns. The mechanical arrangements for accurate gap spacing can be solved, e.g. we have measured on our construction an accuracy of ± 1 mm for all gaps of a 20 stage impulse generator.

Mr. Leroy et al. are right mentioning the advantage of the polytrigatron (a multiple gap system in each stage) concerning the absence of mechanical setting procedures. But on the other hand, there are real disadvantages of the multiple gap system compared with conventional or advanced single gap systems (per stage), because in our mind three kinds of nonlinearities are introduced by the polytrigatron-system:

a) The expected trigger mode of the polytrigatron-system is establishing arcs by a high voltage trigger generator in each stage with a delay time of 50 ns per stage. This trigger mode is effective for all stages of a generator only at low charging voltages. At higher charging voltages only a certain number of stages is really triggered by the predicted mode. The rest of the polytrigatrons- in the upper stages of the generation will be fired by the natural over-voltages of the Marx circuit. It depends on the charging voltage how many stages fire in the predicted mode and how many stages are fired by the natural over-voltages.

The presence of two different firing modes and a different distribution of these two modes versus charging voltage leads to a visible non-linearity of the shape of the generated impulse voltage. Possibly, one can see this non-linearity even in Fig. 1 of the discussion of Mr. Leroy et al. It seems that the shape at 200 kV charging voltage is not the same as at 20 kV charging voltage per stage.

b) The number of arcs in the polytrigatron-system is one order of magnitude higher than in single gap systems. Therefore, the sum of arc-voltage drops is much higher. This leads to another non-linearity versus charging voltage concerning the amplitude of the generated impulse voltage. This was already stated in a paper by Simon and Bishop [3].

c) The polytrigatron tends to extinguish at low current rates, for example under switching impulse voltage conditions near the crest of the wave shape. It is well known that a sub-divided arc has a better cooling behaviour as a single arc of the same length. This effect is advantageous for switching-off purpose, e.g. at arrestors, but it is disadvantageous for switching-on and supporting conductivity.

We agree with the discussors that the dependence of the efficiency from the charging voltage is no limiting factor for the tests they mentioned. But we want to remember that some other tests, e.g. transformer tests, need this absolute linearity. An adequate piloting of the generator to eliminate this non-linearity is not easy, because it seems as if the non-linearity is also different for different impulse shapes, because the arc voltage drop across the polytrigatrons depends on the current.

The top electrode should be dimensidned that no predischarges at switching impulse voltages will occur at the maximum desired voltage. We calculate the static electric field for a certain construction with a computer program [2]. The allowed maximum electrical field strength is approximately 20 kV/cm for the rated switching impulse voltages. But we do not know if this 20 kV/cm is the optimal value and if this value is correct above 3,5 MV switching impulse voltages. We think, it is very important to collect more informations about the critical gradient for the corona inception voltage at different curvatures.

We agree with Mr. Bishop's statement that it is possible to get a trigger range of 24% in series connection of all stages with a generator of 12,8 kJ per stage. But we cannot discuss this in detail, because we do not know the arrangement of the elements in the Marx generator, especially the resistance arrangements.

We also agree with Mr. Bishop that the operation range down to 5% is not necessary for normal testing, but if it is possible, it is no disadvantage. The relative gap setting of our construction has an accuracy of approximately 0.2 mm per stage.

The stability of a single gap against d.c. voltages can be increased by dividing the gap distance in many small gaps together with a corresponding voltage grading. But with this advantage one get a number of disadvantages which are already discussed together with the contribution of Mr. Leroy et al.

It is difficult for us to discuss the question of Mr. Bishop concerning the probability of self-firing, because he only says that he gets an acceptable level. We can say that the probability of self-firing in our system is lower than 2%, which, we say, is acceptable.

REFERENCES

[1] K. Feser: Gedanken zur Stossspannungeserzeugung und Prüftechnik für die Entwicklung von UHV-System. Bull. SEV 64 (1973) 15, s. 911-917.

[2] H. Steinbigler: Anfangsfeldstarke und Ausnutzungsfaktoren rotationssymmetrischer Elektrodenanordnungen in Luft. Diss. TH München 1969.

[3] M. J. Bishop, M. F. Simon: The impulse generators in Les Renardieres. IEEE Trans. on Pow. App. and Syst. Vol. 91 (1972) 6pp. 2366-2376.