Measurements of Electro-magnetic Parameters in Pulsed Power Systems

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***Abstract*—Experimental measurements of parameters like voltage/ electric field, current and magnetic fields associated with a discharge of pulsed power systems is important for many purposes. There are several techniques based on electrical and physical effects in different components and materials that can be used to infer these quantities which can vary by several orders of magnitude in time as well as in amplitude. Features, considerations, relative advantages and limitations of such techniques are discussed here.**

***Index Terms*—Pulsed Power System, Magnetic Field, Magnitude and Amplitude.**

I. INTRODUCTION

Measurement of pulsed current and voltages (as also the associated magnetic field) is of paramount importance for almost all applications involving pulsed power, usually to infer the input or output powers and thereby the system efficiency. The application could be a charged particle beam, generation and heating of plasma and electro-magnetically driven systems like macro-particle accelerators and metal forming. Since the time scales for such transient events could be right from nanoseconds to tens or hundreds of milliseconds as also the amplitude of the quantity to be measured could vary by several orders of magnitude, it is imperative that no single device could suffice in itself for whole range. It is advantageous to have a prior idea of the likely orders of magnitude of the time scale as well as the amplitude.

There are a number of ways to measure the parameters of an electrical system including pick up loops and Rogowski coils, current transformer, Hall probe and Faraday rotation for current or the associated magnetic field. Voltage could be measured using resistive or capacitive or a mixed divider, spark gaps. Optical techniques like Kerr and Pockels' effect could also be used for voltage measurement. These techniques and important considerations and features along with merits and demerits are discussed in the following.

II. PULSED VOLTAGE MEASUREMENT METHODS

Generally voltage dividers which could be resistive or capacitive or a mix of both are quite common for voltage measurement in any pulsed power system. These can reproduce the time as well as amplitude profile quite accurately if deployed properly. In certain cases, when only the peak voltage is of interest, techniques like spark gap which may be spherical or rod type could be sufficient. In addition if no contact with the voltage source is desired than optical techniques like Pockels cell are useful. These methods are briefly described below.

a) Spark Gaps

A spark gap, made to create uniform electrical field between the electrodes, would generally break down by itself (self-breakdown) at a fixed voltage (e.g. a 1 cm for a well finished gap in air at 20°c temperature and 1 bar pressure would breakdown at 30 kV voltage) with small variations if the quality of break down medium is well controlled. This property is used to infer peak voltage delivered by a given source but the gap configuration needs to be carefully designed. For this purpose usually electrodes made in spherical form are more suitable.

Spherical electrode gaps can be horizontally positioned or mounted vertically with one electrode grounded or both electrodes connected to the source (see Fig.1.). Break down voltage in spherical spark gaps is found to be dependent on electrode diameter which is same for both electrodes.

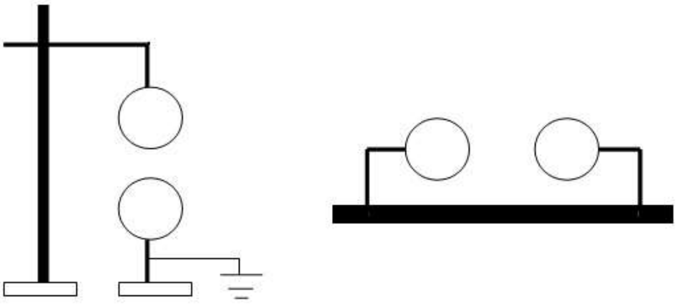


Fig. 1 Sphere Gaps Vertical and Horizontal

Naidu and Kamraju[1] have listed break down voltage for several electrode separations and can be observed to be sensitive to polarity of the electrode. As such the overall position and size of electrodes including attachments need to be carefully designed especially to ensure that break down points are at the minimum distance of the two electrodes. [1]. This can be ensured by uniform curvature and smoothness of the spheres which are generally fabricated out of copper, brass or aluminum. Standard diameters specified for such electrodes are 2,5,6,25, 10, 12,5, 15, 25, 50, 75, 100, 150 and 200 cm. Usually a series resistance is also included with the divider to (i) limit the current and (ii) avoid undesired oscillations in source when break down occurs. Any roughness of the surface, which may take place after a few breakdowns, needs to be smoothed out. At lower voltage the gap may need to be irradiated to ensure uniform breakdown.

There are a number of factors like grounded objects in vicinity, humidity and atmospheric conditions, polarity and rise of the pulse which can affect the breakdown voltage of the gap. The voltage is determined from a set of repetitive data and can yield values within a few percent (3% for gaps of less than half sphere diameter and 5% for gaps more than sphere diameter).A rod gap in form of either a square or circular edge can also be used in the above manner. However their errors are reported to be up to 8%. These also need to be designed with proper tolerances and distances of the assembly.

b) Resistive Voltage Dividers

As the name suggests, a resistive voltage divider consists of two series resistances one with a lower value (R_2) than the other (R_1) and across which the voltage is monitored as per Fig. 2. Voltage (V) across resistance R_2 is a fraction of the voltage (V_0) at source i.e.

$$V = \frac{V_0 R_2}{(R_1 + R_2)} \tag{1}$$

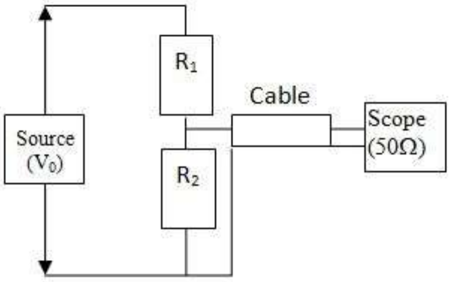


Fig.2 Schematic of a Resistive Voltage Divider

A high ratio of voltage division may be obtained by staging of the divider network[3]. Generally the signal across the output resistor is monitored on a scope in which 50 ohm terminating impedance is generally used since the signal cables are also usually of 50 ohm impedance. It is therefore preferable to have the final stage of monitoring resistance as 50 ohm.

In a resistive divider, there are parasitic capacitances also associated with different elements and connection amongst them or w.r.t. ground. The capacitance of terminating end (C_s) at scope (~10-50 pf) also makes the divider behavior dependent on frequency of signal. To make it independent of frequency, a compensation capacitance (C_c) across R_1 is added in the divider so as to make $R_1C_c= R_2C_s$ which makes the time constants of the two sides equal. In standard high voltage probes, compensatory capacitance is usually provided as variable so as to adjust and compensate for stray capacitance on other connections and cable etc.

At large voltages, the capacitances may become large enough to distort the rise time of a pulse. This is generally dealt by providing guard rings.[1][2]. In measurements of voltage across charged particle accelerators, it may become necessary to operate the dividers in vacuum or insulating medium and consider effects of magnetic flux coupling to the inductance of divider.[3][4][5]

c) Capacitive Voltage Dividers

A capacitive divider consisting of two capacitors in series, is highly useful for fast voltage pulses, though for high voltages the main (small value) capacitance may not be too small in size, and hence may have finite inductance and also resistance but overall size can still be compact as compared to a resistive divider of similar scale. Such dividers have been in use since 1920s. The division ratio would be given similar to the resistive divider except that capacitance values would be interchanged i.e. if voltage is monitored across C_2 while C_1 is the capacitance seeing the high voltage source terminal, then the output voltage would be given as,

$$V = \frac{V_0 C_1}{(C_1 + C_2)}, C_1 \ll C_2 \tag{2}$$

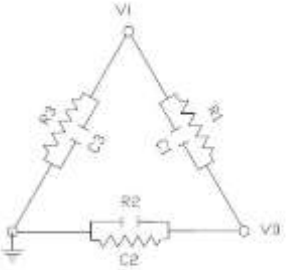


Fig.3. Three Terminal representation of a Capacitive Voltage Divider

Capacitive dividers are more easily designed in co-axial geometry. This geometry also is useful in a way to accurately estimate the values of capacitance, especially of the first stage which any way has to be quite low. It has been reported that if the dielectric of the two capacitors is kept same, the temperature effect on performance is nullified. Effect of fringe electrical fields may be minimized by extending the length of innerelectrode and using guard rings. A three terminal capacitor has been advantageously used for such dividers which may be represented as a combination of three capacitors and three resistances (representing dielectric losses) as shown in Fig. 3. In such cases, with same dielectric used in all the three capacitors, it may be shown that division ratio would simply be given by the relation for a pure capacitive, equation (2) or a pure resistive divider, equation (1). Fast co-axial dividers using titania (TiO_2) as the dielectric medium has also been reported w0ith a rise better than 2.5 ns.

d) Mixed R-C dividers

Many times, it has been found beneficial to employ voltage divider having a combination of resistance and capacitors in parallel or series. In parallel, every capacitor is connected with a parallel resistance and such dividers have been use up to 2 MV voltages. Series combination is found to be much better and devised for voltages of 5 MV and above with rise times of less than 30 ns. In such dividers, the resistive part usually works well for low frequencies while capacitive part responds well to high frequencies.

e) Optical Techniques (Pockels Cell/ Kerr Cell)

These techniques are based on the fact that refractive index of certain materials changes when an electric field is applied across them. The refractive index of such materials may be expressed as a power series w.r.t. an applied electric field E i.e.

$$N = n_0 + a\,E + b\,E^2 + \cdots \tag{3}$$

Here n_o is the ordinary refractive index of the material in absence of any electric field while 'a' and 'b' is the coefficients of such an electro-optic effect in materials. The second term is linear in electric field and gives rise to the so called Pockels effect (after the investigator) while the third term has square dependence and is known as the Kerr effect. The two cases where the applied electric field is parallel or perpendicular to the direction of light beam can give rise to different phase retardations or changes in polarization as usually recorded in this technique and correspondingly termed as longitudinal and transverse Pockels effects respectively. The two effects may be used advantageously depending upon the material in use e.g. KDP crystals may be used in either mode while crystal like Lithium Niobate are mainly used in transverse mode. An advantage of longitudinal operation is that the effect is integrated over the length and hence more sensitive. Systems based on Pockels effect known as Pockels cell have been employed and described in literature[9-10] with further improvements to innovatively use a Pockels cell in combination with a capacitive divider.

The Kerr cell works on the effect of third term of equation (3) i.e. refractive index of light passing with polarization parallel to the electric field and perpendicular to it being different. The phase change may be expressed as $\square = 2\square lbE^2$ for a cell of length l and Kerr constant b and electric field E.

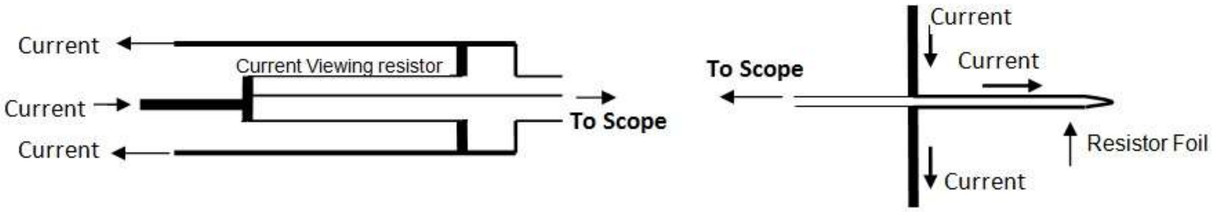
Advantage of such electro-optic techniques is that they are practically immune to EMI interference which is quite common with pulsed power systems. Also since the effects are based on light modulation, they can respond to very high frequencies. However, sometimes such materials (like nitrobenzene used in Kerr cells) may be difficult to handle and may need special care. Voltage that the crystals can withstand may also be limited in some cases like KDP used in Pockels cells.

III. PULSED CURRENT / MAGNETIC FIELD MEASUREMENTS

It is well known that pulsed currents are invariably associated with magnetic fields. This general relationship and association of the two is used to measure the current or the magnetic fields in a system containing the discharge of electrical energy. Based on this principle, a number of techniques like magnetic pick up loops, Rogowski Coils, Current Transformer etc. have been developed. In addition, effect of magnetic field in materials through Faraday rotation is also exploited for current (or magnetic field) measurement. There are techniques like current shunt when used with some care and Hall probe are also employed for such measurements. Such methods are briefly elaborated below.

a) Current Shunt

It is one of the common techniques but requires careful design and connections. Here voltage drop is monitored across a small resistor placed in the path of current. The resistance needs to be really low since voltage drop across it needs to be suitably small for monitoring on a scope when large currents may be flowing through it. Also as live voltage of the transmission is seen by the scope terminal, care is required to avoid ground loops.



(a) **(b)**

Fig.4. Schematic of (a) A Co-axial and (b) A Parallel Plate Current Shunt

In general, inductance of the measurement connection across the resistor needs careful design so as to minimize its inductance and ensure that the shunt resistance >> Inductive impedance. The inductance can be minimized by following a cylindrical co-axial or parallel plate geometry.

In co-axial geometry the current is made to flow in a cylindrical shell within which another thin tube is embedded as seen in Fig. 4(a) while in parallel plate geometry, the current flows through bars into and out of a thin metallic foil resistor across which the output is monitored. The current viewing resistor shell or strip as perFig. 4(b) is usually made out of Nichrome metal due to better hardness and less temperature sensitivity for resistivity. Another configuration for such shunts could the squirrel cage type of return conductor in co-axial geometry.

In these shunts, the thickness of the current viewing resistor needs to be thin enough so that current flows through full thickness i.e. skin depth is more than the resistor thickness. At the same time it has to withstand high electromagnetic force if used at high currents of 100 kA or more. In general to satisfy both the requirements i.e. high frequency and large currents, such sensors become impractically large in size and therefore we need to resort to other forms of measurements.

b) Magnetic Loop (B-dot Probe) and Rogowski Coil

It is well known that pulsed currents are invariably associated with magnetic fields. This general relationship and association of the two is used to measure the current or the magnetic fields in a conductor carrying the discharge of electrical energy. The voltage induced in the secondary (coil or pick up loop) is proportional to the rate of change of flux associated with the conductor which in turn is proportional the product L (dI/dt) with L as the inductance of the pick-up coil. Thus a higher and faster current would result in higher signal voltage. However, in general for this situation, as the induced voltage is proportional to the rate of change of current or the associated magnetic flux, it becomes necessary to integrate the signal either using a RC integrator or numerically using the digitized waveform data. The circuit for such a loop can be represented as shown in Fig. 5 and mathematically written as follows;

$$\frac{d\emptyset}{dt} = L\frac{di}{dt} + iR + \frac{\int_0^t idt}{C} \qquad (4)$$

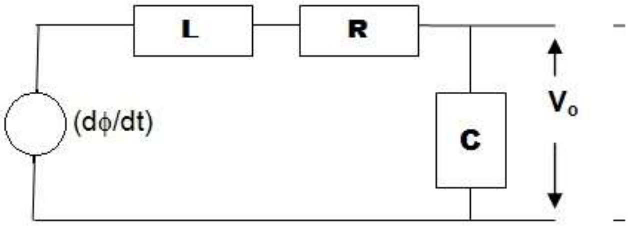


Fig.5. Equivalent Circuit for a Pick loop/ Rogowski Coil

For such loops and coils, L is generally quite small so that condition $\omega L<<R$ is usually applicable for most of the discharge frequencies. For time scales much less than RC i.e. t<<RC, it can be shown[13] that the output voltage produced by such a circuit can be expressed as $V \approx \phi(t)/ RC$. Since magnetic flux is related to current I as $\phi(t) = knI(t)$ where n is the total number of turns in the pick-up loop and k is a factor dependent on the geometry of coil and current distribution, the voltage can finally be expressed as

$$V(t) = \frac{k\, n\, l(t)}{(RC)} \qquad (5)$$

Thus to generate a large voltage for a given current, we can increase the number of turns in the loop but that also increases L, restricting its frequency response. Requirement of t <<RC (for proper integration) also limits the resultant voltage signal. Thus a single turn loop would have high frequency response but small voltage while a multi-turn would lead to opposite effects. Also the constant k being sensitive to the geometry and current distribution needs to be correctly determined. A general method can be to fix the position and orientation of the loop with respect to current path and if possible calibrate it in-situ by discharging a known current profile e.g. a short circuited damped sinusoidal capacitor discharge.

Rogowski coil is another variation of such loops which has a form of multi-turn solenoid wound into the form of a torus preferably onto its own conductor. This form makes it independent of the position or orientation of the primary current to be measured. As per equation (4), if we have a coil and current with frequencies such that $\omega L>>R$ without external C but with a terminating R to satisfy this condition, than the output voltage can be seen to be approximated as so that the output voltage is directly proportional to current. Such a coil (or) loop then becomes self-integrating.

$$V = \frac{d\emptyset}{dt} = \left(\frac{L}{R}\right)\left(\frac{di}{dt}\right) \qquad (6)$$

In many of the pulsed power measurements, it is desirable to provide an electrostatic shield over the windings with a slit towards the inner diameter to permit magnetic field coupling. This considerably reduces errors due to capacitive coupling to large voltage fluctuations but it has been reported to act like a delay line with high frequency limited by the transit time around this delay line.

c) Current Transformer

For fast current pulses, however the restriction $\omega L<< R$ may no longer remain valid in case of large number of turns in Rogowski Coil type of wound coils. In such a situation, self-resistance r of the coil becomes significant and R is chosen so as to satisfy condition $(r + R) << \omega L$. In such a situation equation (6) again becomes applicable with R being equal to (r + R) and the output signal becoming directly proportional to the current. The coil configuration is then known as current transformer. The low frequency limit of this configuration is determined by the requirement of $(r + R) << \omega L$ while upper frequency limit is restricted by the resonant frequency of the internal LC of the coil. The lower frequency limit may be decreased by winding the coil on a Ferrite core thereby increasing the L but this in turn also reduces the upper frequency limit.

d) Hall Probe

These probes work on the principle of well known “Hall effect” in metals and semi-conductors i.e. when a current is made to flow in a metallic plate placed in a magnetic field applied perpendicular to it, the electrons and ions/ holes are deflected to opposite faces of the plate in a direction which is perpendicular to both the current and magnetic field. This charge displacement results in a potential or “Hall voltage” being developed across the face which can easily be measured. This Hall voltage (V_H) can be related to the magnetic flux density B and current I through a relation;

$$V_H = R\left(\frac{BI}{t}\right) \tag{7}$$

Here‘t’ is the thickness of the plate. R is a constant known as Hall coefficient which a property of the material in use. This factor is small for metals but quite high for semi-conductors. A small current is passed through the Hall element and voltage across the surface is registered with additional magnetic concentration through the use of iron core. With proper design, such probes are reported to be useable up to 50 MHz frequencies. In general, such probes can be used for cross calibration of current or magnetic probes since Hall probes in high current or voltage environment generally encountered in pulsed power systems may not make it very convenient for use.

e) Faraday Probe

The techniques is based on the well-known discovery of Michael Faraday that a circular birefringence is introduced in a number of materials subjected to a magnetic field (H) perpendicular to the direction of propagation of light passing through it. This birefringence can be detected by the rotation of the plane of polarization of a linearly polarized light transmitted through the medium. The effect is termed as Faraday rotation and the angle of rotation θ_F in a material of length L embedded in magnetic field H can be described as

$$\theta_F = V \int Hdl \tag{8}$$

where V is referred to as the Verdet Constant which is a characteristic of the material at given wavelength and given as $V= \pi\gamma/(\lambda\ n)$ with γ as the magnetic gyration co-efficient of the material, n as the refractive index in absence of magnetic field and γ the free space wavelength of light under consideration. Although almost every material will have some sensitivity to Faraday rotation, significant effect is provided by certain glasses. The later are therefore normally used either in the form of small solid piece or as used in optical fibers though with a small birefringence. As the optical fibers are relative cheap and easy to handle, one usual way is to warp a number of turns of optical fiber around a current carrying conductor to maximize the rotation. Other glasses such Terbium-Gallium-Garnet (TGG) have high verdant constants in visible region so that a small piece can used as a probe for magnetic field or current with good sensitivity. Such a miniaturized probe has recently been developed by us. There have been a number of reports on recording the Faraday rotation in various ways.

IV. SUMMARY

A number of techniques are available for measurement of voltage and current (and associated electro-magnetic field) which are necessary to characterize a pulsed power system or its application. A brief description of some of such methods suitable for pulsed power in a range from a few kHz to several MHz or more has been provided here. The discussion is mainly focused on the working principle of these techniques with salient features and limitations on their use in desired applications. Details of implementation of a required diagnostic can be looked into several references reported in the literature over the period.

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