RADIO-FREQUENCY IGNITION HAZARDS:
the power available from
non-resonant structures

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Summary

Structures in petrochemical and similar industrial plants can act as inadvertent receiving aerials, leading to a risk of ignition of flammable vapours when strong radio waves are present. The hazard is greatest when the structure is tuned to the transmission frequency. When several transmissions are present, the structure is unlikely to be tuned to more than one transmission at any given time and will tend to discriminate against those to which it is not tuned. The detuning effect may be quantified by a parameter Q. Values of Q have been calculated for a variety of structures from their measured impedance/frequency characteristics.
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1. Introduction

Structures in petrochemical and similar industrial plants can act as inadvertent receiving aerials. When strong radio waves are present, sparks may be generated and there is a risk of ignition of flammable vapours. The power which can be extracted from a structure in the form of a spark is greatest when the structure is either self-resonant or tuned by an external capacitor. The external capacitor might, for example, be the stray capacitance between a pair of separated pipe flanges, or between a crane hook and a load which has just been set down.

When only one strong radio transmission has to be considered, the ignition hazard is usually assessed for the worst case, which occurs when the structure is tuned to the transmission frequency. Both the open-circuit voltage at the terminals of the structure and the power which can be extracted from it are then greatest. If several transmissions are present simultaneously, however, the structure is unlikely to be tuned to more than one of them at any given time, although the possibility of multiple resonance cannot be completely ruled out. The structure will tend to discriminate against those transmissions to which it is not tuned; both the open-circuit voltage and the available power will be less than they would be if the structure were tuned.

This report describes a method for calculating the reductions in open-circuit voltage and available power which occur when a structure is detuned. The actual reduction depends on the impedance/frequency characteristic of the structure and varies considerably from one structure to another. The degree of variation is quantified by a parameter $Q$ defined in Section 4. $Q$ values have been calculated for a variety of structures which have been studied in recent years and the results are also given in Section 4. A set of universal curves showing how the available power varies when structures are detuned is presented in Section 5.

Use of these or similar curves could form the basis of an assessment procedure for multiple transmissions. The maximum power available from each transmission would be calculated first by the method which has been proposed for single transmissions. The structure would then be assumed to be tuned to each frequency in turn. The contribution from the transmission to which the structure is tuned would, of course, be the value already calculated but the contributions from the other transmissions would be reduced by factors derived in this report. The contributions from all the transmissions would then be summed and the greatest power-sum would indicate the most hazardous situation.

2. Theoretical considerations

This section considers how the open-circuit voltage at the terminals of a structure, and the power which can be extracted from it, vary when the structure is detuned.

Fig. 1 (a) shows the equivalent circuit of a

![Fig. 1 (a) shows the equivalent circuit of a structure](image)

(a)

Fig. 1—Equivalent circuit of a structure

(a) structure tuned by external capacitor

(b) tuned structure with spark resistance

(c) simplified equivalent circuit
structure in its simplest form. The generator \( V \) represents the voltage induced in the structure by a particular transmission whose frequency is assumed to be constant. The impedance of the structure at this frequency is \( R + jX \); the impedance at any other frequency will be different. Although the reactance may be of either sign, inductive structures present the greater ignition hazard because an incendiary spark is more likely to be formed when a structure is tuned by a capacitance. The discussion is therefore confined to inductive structures.

### 2.1 Open-circuit voltage

When the structure represented by Fig. 1(a) is tuned by an external capacitor of reactance \(-jx\), the open-circuit voltage \( V_{oc} \) is given by

\[
V_{oc} = \frac{-jxV}{R + j(X - x)}
\]

(1)

The modulus of \( V_{oc} \) is

\[
|V_{oc}| = \frac{Vx}{\sqrt{R^2 + (X - x)^2}}^{1/2}
\]

(2)

and is greatest when \( x = (R^2 + X^2)/X \). When its value is

\[
V_{max} = \frac{V}{R} \left( R^2 + X^2 \right)^{1/2}
\]

(3)

The variation in open-circuit voltage, relative to its maximum value, is therefore described by the expression

\[
\frac{|V_{oc}|}{V_{max}} = \frac{Rx}{\sqrt{R^2 + (X - x)^2}^{1/2}(R^2 + X^2)^{1/2}}
\]

(4)

### 2.2 Available power

When a spark is formed across the tuning capacitor, it can be represented by a resistance \( r \), as shown in Fig. 1(b). The power dissipated in the spark is greatest when the impedance of the parallel combination of \( r \) and \( x \) is equal to \( R - jX \), i.e. to the conjugate impedance of the structure. This condition is satisfied when

\[
r = \frac{R^2 + X^2}{R} \quad ; \quad x = \frac{R^2 + X^2}{X}
\]

(5)

The maximum power \( P_0 \) is equal to \( V^2/4R \).

It is worth noting that identical values of \( x \) result both in maximum open-circuit voltage and maximum available power. These are the two parameters of most interest when ignition hazards are concerned and it is fortunate that there is no ambiguity about the value of capacitance which is required to resonate a structure at any given frequency.

If the structure is detuned, mismatch will occur between the spark resistance and the structure and the available power will be less than \( P_0 \). It has been shown that the power dissipated in a resistance driven via an impedance is greatest when the resistance is equal to the modulus of the impedance.\(^2\) This is known as the modulus-match condition and it is used here to calculate the maximum power available from the structure when it is detuned.

The impedance through which the resistor \( r \) is driven is the parallel combination of the structure impedance \( R + jX \) with the tuning reactance \(-jx\). This is represented by the impedance \( Z \) shown in Fig. 1(c). The generator voltage of Fig. 1(c) is equal to the open-circuit voltage \( V_{oc} \) of Fig. 1(a).

The modulus-match power \( P_{mm} \) is given by

\[
P_{mm} = \frac{|V_{oc}|^2}{2(R' + |Z|)}
\]

(6)

where \( R' \) is the resistive part of \( Z \). Values of \( R' \) and \( |Z| \) are calculated most conveniently from the expression \( Z = V_{oc}/I_{oc} \), where \( I_{oc} \) is the current which flows when the terminals are short-circuited. Referring to Fig. 1(a) it can be seen that

\[
I_{oc} = \frac{V}{R + jX}
\]

(7)

From Equations (1) and (7) it therefore follows that

\[
Z = \frac{V_{oc}}{I_{oc}} = \frac{-jx(R + jX)}{R + j(X - x)}
\]

\[
R' = \frac{x^2R}{R^2 + (X - x)^2}
\]

\[
|Z| = \frac{x(R^2 + X^2)^{1/2}}{\sqrt{R^2 + (X - x)^2}^{1/2}}
\]

(8)

Substitution of Equations (1) and (8) in Equation (6) then gives the following result

\[
P_{mm} = \frac{V^2}{2 \left( R + \frac{1}{x} \sqrt{R^2 + (X - x)^2} \left( R^2 + X^2 \right)^{1/2} \right)}
\]

(9)
Equation (9) describes how $P_{\text{max}}$ varies as the tuning reactance varies. When $x = (R^2 + X^2)/X$ (the condition for resonance), Equation (9) simplifies to $V_0^2/4R$, which is equal to $P_0$. It follows, therefore, that the variation of available power, relative to its maximum value, is described by the equation below

$$\frac{P_{\text{mm}}}{P_0} = \frac{2R}{R + \frac{1}{x} [R^2 + (X - x)^2]^{1/2} (R^2 + X^2)^{1/2}}$$

(10)

2.3 The relationship between voltage and power reduction

When a structure is detuned, the open-circuit voltage is reduced by a factor $n$ (where $n > 1$) equal to $[V_{\text{max}}/V_0]$, given by the reciprocal of Equation (4). Similarly, the available power is reduced by a factor $m$ (where $m > 1$) which is given by the reciprocal of Equation (10). From the two inverted equations it follows that

$$m = \frac{1}{2}(1 + n)$$

(11)

This relationship between the voltage and power reductions which occur when a structure is detuned is independent of the type of structure or its impedance. It is of interest to note that if the voltage is reduced by 3 dB ($n = \sqrt{2}$), the available power is reduced by only 0.8 dB.

3. The characteristics of a typical structure

Fig. 2 shows the impedance/frequency characteristic of a large mobile crane, which can be regarded as a typical structure. The impedance was measured between the crane hook and the ground and an equivalent circuit was derived. The curves of Fig. 2 were calculated from the equivalent circuit.

The crane formed a large loop with a perimeter of 82 m and was inductive at all frequencies below 1.33 MHz, where it was self-resonant. The values of tuning capacitance which give maximum open-circuit voltage were calculated from the impedance/frequency characteristic of the crane and are shown in Fig. 3. As explained in Section 2.2, these values of capacitance also tune the crane for maximum available power.

If a transmission of frequency $f_1$ induces a voltage in the crane, the open-circuit voltage will be greatest when the capacitance has the value given by Fig. 3 for this frequency. If the tuning reactance $x$ is then varied, the open-circuit voltage and modulus-match power will decrease in the manner described by Equations (2) and (9). Every value of $x$...
corresponds to a capacitance equal to $1/(2\pi f \nu x)$ and this capacitance will resonate the crane at some other frequency $f$ which can also be read from Fig. 3. Curves showing how $V_{oc}$ and $P_{mm}$ vary with $f$ can therefore be drawn.

Fig. 4 shows curves drawn in this way, normalised to the maximum voltage or power. For example, the curve labelled $f_t = 1.1$ MHz in Fig. 4(a) shows how the open-circuit voltage due to a 1.1 MHz transmission would vary if the structure were tuned through a range of frequencies. The corresponding curve of Fig. 4(b) shows how the available power would vary. The two curves therefore show how the crane would discriminate against a 1.1 MHz transmission if it were tuned to some other frequency.

5. Comparison of different structures

Curves of the type shown in Fig. 4 have been calculated from the measured impedances of a number of structures having a wide range of $Q$ values. Following Terman, the curves have been compared by plotting voltage and power as a function of

$$f = \frac{f_t Q}{f_t}$$

4. The parameter $Q$

Fig. 4 shows that the curves for frequencies between 0.9 and 1.3 MHz are similar in shape and width, despite the considerable variation in crane impedance over this frequency range. Curves calculated for other structures, however, differ considerably in width. To enable structures to be compared, some parameter is required to describe the width of the curves.

It is proposed here that a suitable parameter would be

$$Q = \frac{f_t}{\Delta f}$$

where $f_t$ is the transmission frequency and $\Delta f$ is the difference between the two frequencies at which the structure resonates, when the open-circuit voltage at $f_t$ has fallen by 3 dB. The parameter is denoted by $Q$ because it is closely related to the $Q$-factor of a tuned circuit.

As an example, consider the curve for $f_t = 1.1$ MHz shown in Fig. 4(a). The open-circuit voltage falls by 3 dB when the structure is tuned to 1.050 and 1.155 MHz. Thus $\Delta f = 0.105$ MHz and $Q = 10.5$.

Values of $Q$ for a variety of structures have been calculated by the method described in Section 3, the calculations being based on measured impedances. The results are shown in Fig. 5. It will be seen that a wide range of values is encountered. There is no obvious connection between the value of $Q$ and the efficiency of a structure as a receiving aerial. All that can be said is that the larger values of $Q$ tend to be associated with the more efficient structures. Fig. 5 shows that, in many cases, the $Q$ increases as

\[\text{Fig. 4—Effect of tuning a large mobile crane over a range of frequencies}\]

\[(a) \text{ open-circuit voltage}\]

\[(b) \text{ available power}\]
where \( f \) is the frequency to which the structure is tuned. This ensures that the peaks of all curves are of similar width.

Fig. 6 shows curves of \( P_{\text{rms}}/P_0 \) drawn on this basis for three structures with very different \( Q \) values. The full line is a composite curve for the crane described in Section 3, the left hand half (labelled \( Q = 11 \)) being calculated for a transmission frequency of 1.2 MHz, and the right-hand half for 0.9 MHz. The two curves are almost identical where they overlap. As expected, all the curves tend to co-incide near their peak.

Fig. 6 suggests the possibility of calculating a set of power curves for specified \( Q \) values. It has been found that the curves for real structures shown in Fig. 6 are consistent with a set of curves, shown in Fig. 7, which have been calculated for simple tuned circuits by a method described in the Appendix. It seems reasonable to assume, therefore, that Fig. 7 could be used to describe the effect of detuning any type of structure, provided its \( Q \) is known.

Although a similar set of curves could be drawn for the variation of open-circuit voltage, the latter can be derived directly from Fig. 7 with the help of Equation (11).
6. Conclusions

If a structure is detuned, the open-circuit voltage and available power are less than they would be if the structure were tuned. The voltage and power reductions are related by a simple formula which applies to all structures.

The sharpness of the detuning effect is a characteristic of the structure. It may be described by a parameter $Q$ which is closely related to the $Q$-factor of a tuned circuit; the larger the value of $Q$, the sharper the detuning effect. $Q$ values for typical structures lie within the range 2 to 50. There is no obvious connection between the $Q$ of a structure and its efficiency as a receiving aerial.

Voltage and power reductions calculated for real structures can be simulated very closely by values calculated for simple tuned circuits having the same $Q$ values. A set of curves derived from simple tuned circuits could therefore be used for ignition-hazard assessments when multiple transmissions have to be considered, provided the $Q$ factors of the structures are known.

7. Acknowledgement

Thanks are due to Mr D W Widginton of the Research and Laboratory Services Division of HSE, Sheffield, for a number of helpful discussions.

8. References

1. Draft British Standard on radio-frequency ignition hazards, Section on “Methods of Assessment” (to be published).

2. WIDGINTON, D.W., Private communication.


9. Appendix: Voltage and power reduction for a simple tuned circuit

A formula showing how the open-circuit voltage at the terminals of a simple tuned circuit, due to an induced voltage of frequency $f_s$, varies when the circuit is tuned to other frequencies, is derived in this appendix. It is also shown that the parameter $Q$ defined in Section 4 is approximately equal to the $Q$-factor of the tuned circuit.

Consider a simple tuned circuit which can be represented, at frequency $f$, by Fig. 1(a). The capacitor is assumed to be lossless and the impedance of the inductive component is therefore $R + jX$. Assuming that the $Q$-factor of the circuit is independent of frequency, the impedance of the inductive component at any other frequency $f$ is equal to $(R + jX)(f/f_s)$. The capacitor which tunes the circuit for maximum voltage at this frequency has a value (at $f$) given by

$$X_c = \frac{R^2 + X^2 f}{X} f_s$$  \hspace{1cm} (14)

At the transmission frequency $f_s$, the reactance of
this capacitor is

$$x = \frac{R^2 + X^2}{X} \left( \frac{f}{f_i} \right)^2$$  \hspace{1cm} (15)$$

The reactance given by Equation (15) can now be considered as the reactance \(x\) shown in Fig. 1(a). If this value is substituted in Equations (2) and (9), it is possible to calculate how the values of \(V_{oc}\) and \(P_{onm}\) observed at the frequency \(f_i\) vary as the circuit is tuned to other frequencies.

It is of interest to determine the two frequencies to which the circuit tunes when the open-circuit voltage \(V_{oc}\) falls by 3 dB at the frequency \(f_i\). If \(|V_{oc}/V_{max}|\) is equal to \(1/\sqrt{2}\), Equation (4) leads to a quadratic in \(x\) whose solutions are

$$x = \frac{X^2 + R^2}{X} \pm R$$ \hspace{1cm} (16)$$

The two frequencies are given by equating this value of \(x\) to the reactance given by Equation (15), so that

$$\left( \frac{f}{f_i} \right)^2 = \frac{X}{X \pm R} = \left( 1 \pm \frac{1}{Q_L} \right)^{-1}$$ \hspace{1cm} (17)$$

where \(Q_L\) is the \(Q\)-factor of the inductive component, equal to \(X/R\). If the two frequencies are denoted by \(f_1\) and \(f_2\), the following result is obtained for the parameter \(Q\) defined in Section 4

$$\frac{1}{Q} = \frac{\Delta f}{f_i} = \frac{f_1 - f_2}{f_i}$$

$$= \left( 1 - \frac{1}{Q_L} \right)^{-1/2} - \left( 1 + \frac{1}{Q_L} \right)^{-1/2}$$  \hspace{1cm} (18)$$

If the terms on the right-hand side of Equation (18) are expanded binomially, it can be shown that

$$\frac{1}{Q} = \frac{1}{Q_L} + \frac{5}{8Q_L^2} + \cdots$$

Thus \(Q\) is approximately equal to \(Q_L\), the error being greatest when \(Q\) is small. For example, if \(Q_L = 5\), then \(Q = 4.87\), a difference of 2.5%.

The variation of \(V_{oc}\) can be expressed as a function of \(f/f_i\) by substituting the value of \(x\) given by Equation (15) into Equation (4); the result is

$$\left| \frac{V_{oc}}{V_{max}} \right| = \frac{(1 + Q_L^{1/2}\left( \frac{f}{f_i} \right)^2}{Q_L\left( 1 + \left[ Q_L - \left( \frac{Q_L + 1}{Q_L} \right)\left( \frac{f}{f_i} \right)^2 \right]^{1/2} \right)}$$  \hspace{1cm} (19)$$

For values of \(Q > 5\) little error results if \(Q_L\) is replaced in Equation (19) by \(Q\). For smaller values of \(Q\) the appropriate value of \(Q_L\) should be derived from Equation (18); for example, if \(Q = 2\), then \(Q_L = 2.28\).

Although a rather more complicated expression can be derived for \(P_{onm}/P_0\), it is more convenient to calculate the power ratio directly from \(|V_{oc}/V_{max}|\) with the help of Equation (11).