Lecture # 11

Generation of High Voltage Impulse

Impulse Voltage

Electrical insulation often experiences transient overvoltages during their service life besides the normal operating voltages for which they are designed. Most of these transient overvoltages are impulsive in nature having magnitude several times the normal voltages, persisting for fraction of second. However, these transient overvoltages abnormally stress the insulators during this short-duration that may have disastrous consequences. An impulse voltage is unidirectional in nature that rapidly rises to a maximum or peak value and then gradually drops to zero. Most transient overvoltages are due to lightning and switching. The basic difference between the lightning and switching impulses are the magnitudes and the rise-times. Lightning impulses have order of magnitude much greater than switching impulses and are also much steeper. Both switching operations and lightning strokes produces traveling waves; that travel along the transmission line conductor and induces transient overvoltages across the insulators. Electrical insulation must therefore be able to withstand the impulse voltages due to switching and lightning besides the normal power frequency voltages or DC voltages in the case of HVDC system. An insulator must therefore be tested with impulse voltage, to determine the impulse voltage withstand capability and to establish its capability to withstand transient over-voltages.

Standard Impulse Waves

In order to generate standard impulse voltages for testing purpose, it is necessary to understand the characteristics of both switching and lightning impulses. Overvoltages caused by lightning may be of either positive or negative polarity; however, polarity has little or no effect on the breakdown strength. The impulse voltage is standardized according to the nominal wave-front time (defined as the time taken for the impulse voltage to rise from 10% to 90% of its maximum value) and the nominal wave-tail time (defined as the time taken for the impulse to decay to 50% of its maximum value). The shape of a standard impulse is shown in Figure (1), which is generally divided into two portions; the rising portion and the decaying portion designated by times t_1 and t_2 respectively. As such, it is then defined as t_1/t_2 µs-wave or simply t_1/t_2 wave. The unit microsecond incorporated is an indication that the two times are in microseconds.

It has also been observed that overvoltage surges of impulsive nature can be represented as a resultant of two exponential waves and is generally expressed as:

$$v(t) = V[\exp(at) - \exp(bt)] \qquad 1$$

Where a and b are inverse of time constants and are evaluated for impulse generator by knowing the values of resistors and capacitors.

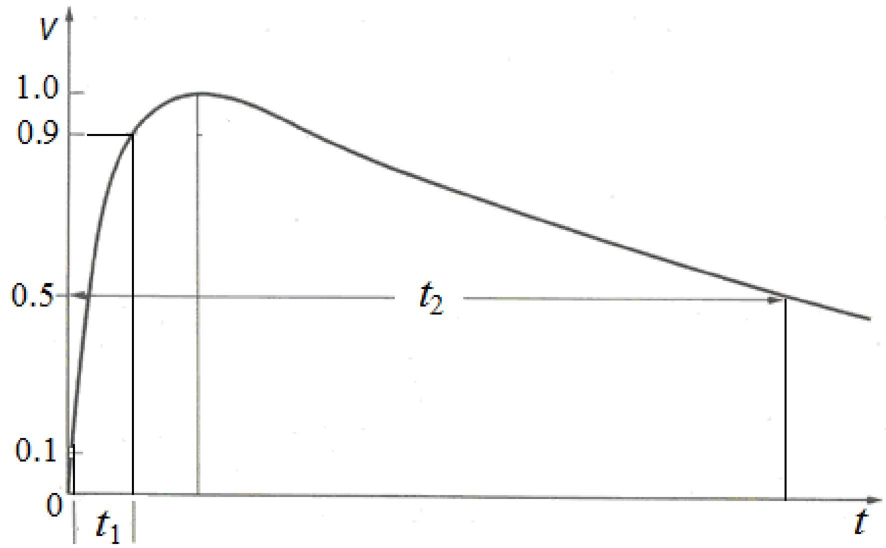


Figure 1: Standard Impulse Waveform

For testing purposes, it is essential to have a standard waveform generated with specifications that can simulate voltage surges produced as a result of switching operations or lightning strokes. In practice there are different specifications for times t_1 and t_2, based on standards and can be adjusted from the parameters of the impulse voltage generator.

A British Standards specification for lightning impulse is defined as 1/50 μs impulse wave, with an allowed tolerance of ±50% in the wave-front time and ±20% in the wave-tail time. According to American Standards a lightning impulse is defined by 1.5/40 μs wave with an allowed tolerance of ±0.5μs in the wave-front time and ±10μs in the wave-tail time.

The standard switching impulse voltage 250/2500μs has a time to peak of 250μs (tolerance: ±20 %) and a time taken to decrease to 50% of peak value of 2500μs (tolerance: ±60 %). In some cases, the rise time may be taken as 300us and decay time as 3500us.

Exponential Wave Generator

A circuit of a simple exponential wave generator is shown in Figure (2). The capacitor C is charged through the high series resistor R_1 so that the capacitor gradually charges up to the supply voltage V. During the charging process there will be a small voltage across the load R_2, which decay to zero as the capacitor charges. Once the capacitor is charged, the source voltage is disconnected. The circuit only consists of a loop formed by R_2 and C through the switch S. If the switch S is now closed at $t = 0$ the capacitor will discharge through R_2. If $i(t)$ is the discharge current due to closure of switch S in the circuit containing C and R_2, then the loop equation of the circuit after the switch is closed ($t > 0$) as obtained by applying Kirchoff's voltage law to the loop containing R_2 and C is:

$$R_2 i(t) + \frac{1}{C}\int i(t)dt = 0$$

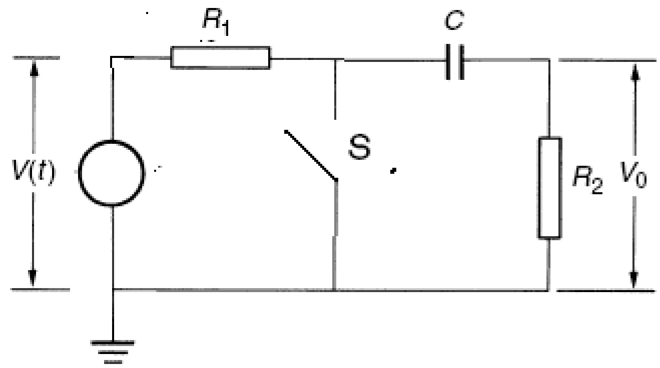


Figure 2: Exponential Wave Generator Circuit

Taking the time derivative of both sides of the loop equation, the differential equation is obtained, which can be solved for the loop current *i*(*t*) that is:

$$\frac{di(t)}{dt} + \frac{i(t)}{R_2 C} = 0 \qquad 2$$

Eq (2) is a homogeneous first-order differential equation with no particular solution. The complete solution will only contain the complementary or transient portion, which has a general form:

$$i(t) = k\exp\left(-\frac{t}{R_2 C}\right) \qquad 3$$

The value of k is determined from the state of capacitor voltage at the time of closing the switch at $t = 0$, so that: $k = \frac{V}{R_2}$. Therefore:

$$i(t) = \frac{V}{R_2}\exp\left(-\frac{t}{R_2 C}\right) \qquad 4$$

The voltage V_0 across the resistor R_2 is:

$$V_0 = V\exp\left(-\frac{t}{R_2 C}\right) \qquad 5$$

The charge on the capacitor discharges through the resistance R_2 so that instantaneously the voltage across R_2 rises to V and will then decay exponentially according to the equation as $V\exp(-t / R_2 C)$, where $R_2 C$ is the time constant of the discharging circuit. For this waveform, the rise-time (wave-front time) is very small, and the time to decay to 50% of peak value (wave-tail time) corresponds to $CR_2 \ln(V/V_0)$. The closing and then opening of switch with appropriate timing will produce the output voltage, which will have an approximate shape as shown in Figure (3).

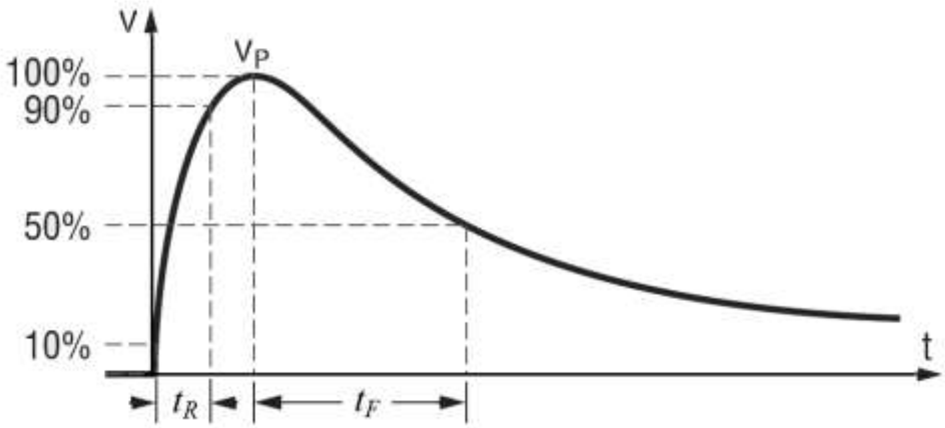


Figure 3: Output Waveform

The rise-time t_R of the exponential wave is the time in which the voltage increases from 10% to 90% of its peak value V_p. The decay-time t_F refers to the time in which the voltage decays to 50% of its peak value.

Example 1: Design a high voltage exponential wave generator to incorporate an HVDC input source, a rectifier supplied by a 1.5kVA, 220V/35kV, single-phase transformer. The exponent wave at the output should have a decay time smaller than 10μs. Choose an appropriate value of the input resistor so that the voltage drop in the exponential generator must not exceed 1%. Assume a voltage drop of 2% in the rectifier.

Solution:

The input voltage to the generator is derived from a rectifier incorporating a 1.5kVA, 220V/35kV transformer.

The exponential wave that can be obtained will have an output less than 35kV due to the voltage drops in the rectifier circuit and exponential wave generator circuit. A voltage drop of 2% in the rectifier circuit will produce an input voltage of: $35-0.02(35)$, which is 34.3kV. To calculate the value of input resistor to limit the voltage drop in the exponential generator circuit to 1%, it is essential that we should know the maximum current that can flow in the circuit. From the kVA rating, the current in the input circuit will be:

$$I = \frac{1.5}{35} = 42.85\text{mA}$$

The permissible voltage drop in the exponential generator is 1% of the input voltage supplied that is: $0.01(34.3) =$ 0.343kV or 343 volts. This voltage drops in the input resistor R_1. Thus:

$$R_1 = \frac{343}{42.85 \times 10^{-3}} = \mathbf{8k\Omega}$$

We can choose a suitable value of the capacitor that can be constituted in the output circuit to give us a value of the output resistor. Arbitrary choosing C = **1nF**, then for a time constant of 10μs, the value of the output resistor R_2 is:

$$R_2 = \frac{10\times10^{-6}}{10\times10^{-9}} = \mathbf{1k\Omega}$$

The output voltage across the output terminals of the generator will be: $(34.3-0.343)\approx$ 34kV.

Single-stage Impulse Generator

The schematic arrangement of a single-stage impulse generator is shown in Figure (4). The input section consisting of a capacitor C, which charges through a HVDC source to some pre-determined voltage V (10kV to 100kV typically). The output section consists of combination of two resistors R_1 and R_2, referred to as wave-front and wave-tail control resistors. R_1 is low value of the order of a few Ohms, whereas R_2 is having a high value of the order of kilo Ohms. The output capacitor C_0 may be the capacitance of a test object, such as cable or other insulator together with any stray capacitance. The wave-front and wave-tail times of the impulse voltage is controlled by adjusting the two resistors R_1 and R_2 through time constants R_1C_0 and R_2C respectively. The input and output sections are isolated by a spark gap G. The operation of the circuit is initiated by the spark-over of the gap G.

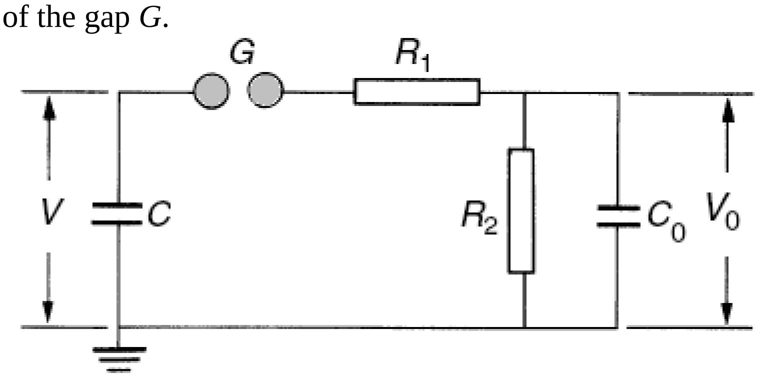


Figure 4: Single Stage Impulse Generator

The input capacitor C is charged gradually from an HVDC source, generally up to about 10kV to 100kV. Once charged, the HVDC source is disconnected either manually or automatically. The spark gap G is gradually closed until it breaks down, which allows the capacitor C to discharge upon C_0 through the resistors R_1 and R_2. As the gap G flashover, it discharges the capacitor and an impulse is subjected on the test object represented as output capacitor. The output voltage is governed by the expression:

Or $$v_0(t) = V_m\left[\exp\left(-\frac{t}{R_2C}\right) - \exp\left(-\frac{t}{R_1C_0}\right)\right] \qquad 6$$

The voltage efficiency of impulse generator can be obtained by an expression:

$$\eta = \frac{V_p}{V} \qquad 7$$

Where V_p is the peak value of the output impulse wave.

In order to generate impulse voltages with a peak value of the order of megavolt, the use of single-stage impulse generator is often a disadvantage because of the following major reasons:

1. The high peak voltages to be generated require a large HVDC supply for charging the input-stage capacitor.
2. Above about 200 kV, the charging capacitors and resistors become very heavy and expensive.

Because of the above disadvantages, most single-stage impulse generators are limited for the production of impulse with peak values of up to about 200 kV.

Multi-stage Impulse Generator (Marx Generator)

In order to produce impulse voltages of the order of several megavolts, a number of single-stage impulse generators are cascaded to form multistage impulse generator, also known as Marx generator. Each stage of a multistage impulse generator is a single-stage impulse generator, consisting of a charging capacitor, a spark gap and two resistors. The number of spark gaps or the number of charging capacitors thus connected is an indication of the number of stages. In order to understand the production of an impulse, consider a four-stage impulse generator as shown in Figure (5).

The working of the generator is as follows: Referring to Figure (5), the HVDC source voltage V is applied at A. This allows simultaneous charging of the stage capacitors from C_1 to C_4 through resistors R. Thus each capacitor retains a charge equal to the potential difference V applied. It must be mentioned here that all the right-hand terminals in Figure (5) that is terminals B, C, E, G and J are all at the ground potential, whereas terminals A, D, F and H are all at a potential of the HVDC source. The triggering of the generator to produce an impulse is initiated by the spark-over of the first spark gap G_1. When G_1 spark over, it places short-circuit across A and B thus allowing discharge of capacitor $C_{1.}$ This makes the capacitor voltage on the plate connected to A from V to zero and at the same time, allowing a swing of $-V$ thus making the potential at terminal C to change from zero to $-V$. This potential swing to $-V$ at terminal C produces a potential difference of $2V$ across the spark gap G_2 (the plate of capacitor C_2 still retains its charge during discharge of C_1 owing to the resistance R connected between A and D), which causes the spark gap G_2 to spark-over. The spark-over of gap G_2 allows the discharge of capacitor C_2 in a similar manner as G_1 allowed discharge of C_1. The voltage swing in this case places a potential of $-2V$ at the terminal E thus producing a potential difference of $3V$ across the spark gap G_3 to spark-over instantly that causes the capacitor

C_3 to initiate its discharge. The discharge of capacitor C_3 causes a voltage swing from zero to $-3V$, instantly causing a potential of $-3V$ at terminal G thereby resulting in a potential difference of $4V$ across spark gap G_4, which immediately breaks down and thus discharges capacitor C_4. The discharge of capacitor C_4 allows a voltage swing from zero to $-4V$ resulting in a potential of $-4V$ at terminal J.

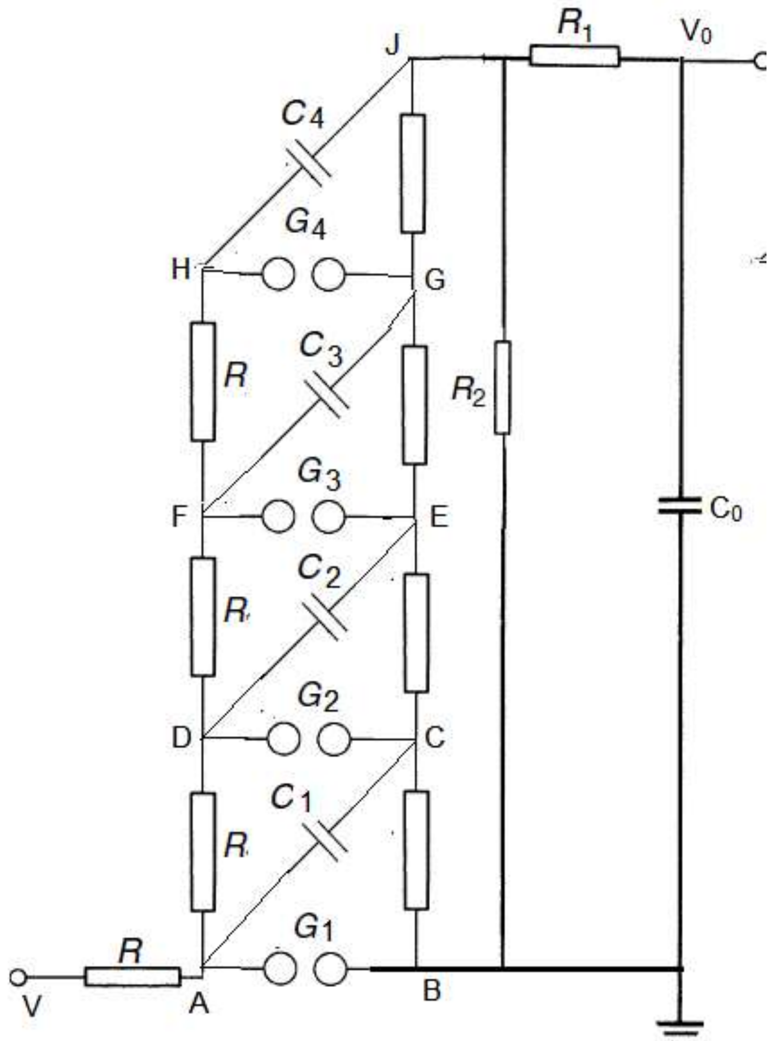
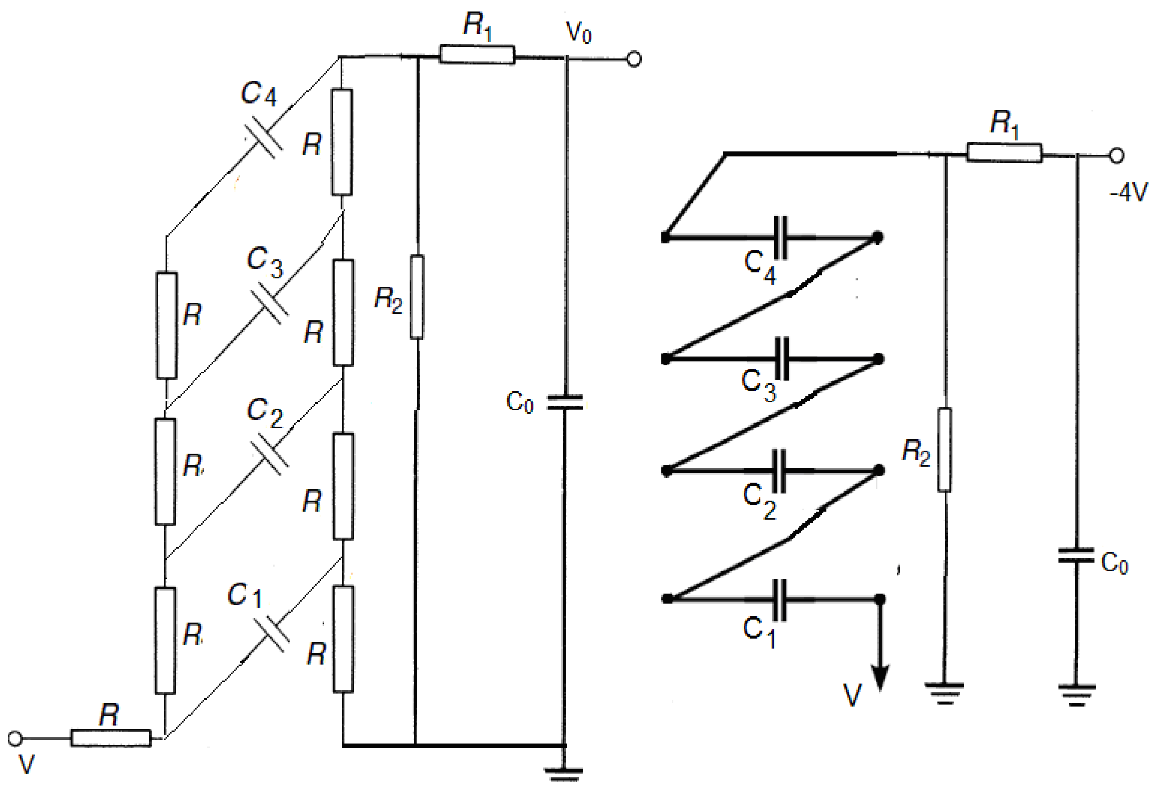


Figure 5: 4-stage Impulse Generator

At the output terminal, a voltage equal to four-times the input charging voltage from HVDC source is thus impressed on the test object with capacitance C_0. Instead of producing output voltage having negative polarity, reversing the terminals of the HVDC test-source in the input section can produce a voltage of positive polarity at the output terminals.

The sequential breakdown of spark gaps one after the other is in very quick succession and thus allows all the capacitors to discharge in series. Since each capacitor is retaining the same charge and so are charged to voltage V. Thus a voltage equal to V time the number of capacitors is thus applied across the test object connected in the output. In the multi-stage impulse generator all the stage capacitors are charged in parallel due to open-circuited spark gaps and the discharged in series due to short-circuited (because of spark-over) spark gaps. The process of parallel charging and series discharging of the capacitors is illustrated with the help of equivalent circuit for charging all capacitors in parallel and then discharging them in series as shown in Figure (6).



(a) **(b)**

Figure 6: (a) Parallel Charging (b) Series Discharging

The resistors R_1 and R_2 respectively are employed for wave-front and wave-tail control. In general if the number of stages in the multistage impulse generator are n (equal to the number of capacitors or spark gaps), then the voltage V_0 impressed across the test object will be:

$$V_0 = nV \qquad 8$$

Thus cascading several similar single-stage impulse generators can produce a very high voltage of the order of several megavolts. If for example ten similar single stage 100 kV impulse generators are cascaded to form a multistage configuration, a voltage of 1MV can be produced.

A multistage impulse generator can generally be represented as an equivalent single-stage generator as shown in Figure (7). In a practical impulse generator circuit, the nominal voltage is defined by the peak voltage and the nominal energy is defined by the maximum stored energy.

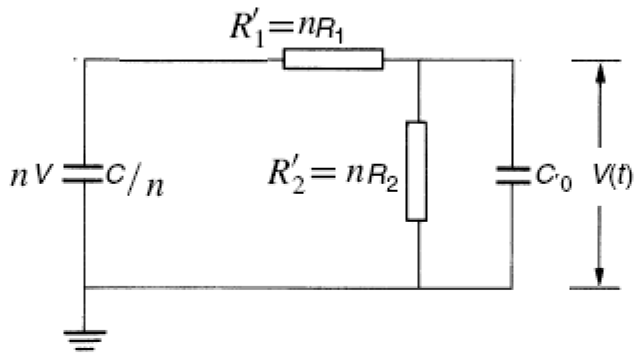


Figure 7: Equivalent Circuit of *n*-Stage Impulse Generator

The equivalent parameters for an *n*-stage generator to be represented as a single-stage generator configuration are as follows:

$R_1' = n\,R_1$
$R_2' = n\,R_2$
$C' = C\,/\,n$

Example 2: An impulse generator is composed of 4-stages with each stage having a capacitance of 0.1 μF. If the charging voltage is 100 kV per stage, calculate the energy output of generator.

Solution:

Given that: $C = 0.1\mu F$ per stage and $V = 100kV$. Number of stages = $n = 4$. Total generator capacitance when discharging = $\frac{C}{n} = \frac{1}{4} \times 0.1 \times 10^{-6} = 25nF$. Total voltage when discharging $V_0 = nV = 4 \times 100 = 400kV$. Therefore, energy is:

$$\xi = \frac{1}{2} C V_0^{\,2} = \frac{1}{2} \times 25 \times 10^{-9} \times (400 \times 10^{3})^2 = \mathbf{2.0\ kJ}$$