Application Guide
High Impedance Differential Protection
Using
SIEMENS 7SJ602

1 INTRODUCTION

This document provides guidelines for the performance calculations required for high impedance differential protection.

2 PROCEDURE FOR PERFORMANCE CALCULATIONS

2.1 Data Required

2.1.1 System Information

a) Maximum through fault current for external faults $I_{k,max,thr}$

b) Maximum internal fault current $I_{k,max,int}$

c) Minimum internal fault current $I_{k,min,int}$

2.1.2 Current Transformer Information

The CTs used in this type of scheme should be of the high accuracy and low leakage reactance type according to IEC Class PX, TPS or BS Class X.

a) Turns ratio $K_n = \frac{I_{pn}}{I_{sn}}$ (all CTs must have the same ratio)

b) Secondary resistance R_{ct}

c) Magnetising curve $V_{mag,rms}(I_{mag,rms})$ or at least
   Knee-point voltage V_{knee} and
   Magnetising current at knee-point voltage I_{knee}

d) CT lead loop resistance R_L

The lead resistances are either given in the tender document or can be calculated from the layout drawings. In the worst case a maximum lead resistance can be estimated and specified as a maximum allowable.

2.1.3 Protection Relay Information

a) Operating current or current setting range I_{set}

b) Operating voltage or relay burden expressed in voltage V_r or resistance R_r

2.2 Fault Setting

2.2.1 Relay Setting Voltage

The protection relay must remain stable under maximum through fault conditions, when a voltage is developed across the protection buswires due to the fault current and CT saturation. The relay setting voltage must be made equal or greater than this maximum voltage for the protection to remain stable. That is:

$$V_{set} \geq V_{stab} \quad (1)$$

where

V_{set} = relay setting voltage

V_{stab} = stability voltage

The fault current may contain a transient d.c. component current, or there could be high remanence in the CT core either of which can cause saturation of the current transformer core and thus distortion of the secondary current. Therefore, in order to calculate the required setting voltage for stability, it is assumed that one of the protection CT's saturates totally. Under these conditions current balance is lost and the healthy CTs are driving current through the parallel impedance of the saturated CT plus lead loop resistance and the protection relay. By setting the voltage setting of the relay above the maximum voltage developed across the buswires then stability is assured. The saturated CT impedance is represented by its secondary winding resistance, and the maximum lead loop resistance between any CT and the relay must be used in the calculation of V_{set}.

For the simple case of two current transformers, the voltage developed across the relay is given by:

$$V_{set} \geq \frac{I_{k,max,thr}}{K_n}\left(R_{ct} + R_L\right) \qquad (2)$$

In most practical systems where more than two current transformers exist, the same equation is used based on the fact that this represents the most onerous condition. R_L must be the highest loop resistance between any CT and the Relay.

In addition, the setting voltage must be lower than half of the knee point voltage of any CT in the protection scheme.

$$V_{set} \leq \frac{V_{knee}}{2} \qquad (3)$$

The criteria outlined above establishes maximum and minimum values for the relay setting voltage.

2.2.2 Stabilising Resistor

The relay 7SJ602 requires a stabilising resistor to be connected in series for use as high impedance differential protection relay. This approach increases the relay circuit voltage setting. The resistor can be sized as follows:

$$V_{set} - V_r = I_{set} R_{stab} \qquad (4)$$

where

R_{stab} = stabilising resistance required

Using the maximum and minimum voltages calculated by (2) and (3), a resistance range can be calculated from which a suitable resistor can be chosen. Typically the next highest standard value or a variable resistor is used. Using the actual values fitted the actual relay circuit setting voltage can be calculated.

2.2.3 Relay Setting Current

The primary operating current (fault setting) may be calculated using the practical approximation:

$$I_{p,set} = K_n \cdot \left(N_{ct} \cdot I_{e,set} + I_{set} + I_{var}\right) \qquad (5)$$

where

$I_{p,set}$ = primary fault setting

N_{ct} = number of CTs in parallel

$I_{e,set}$ $= I_{knee} \frac{V_{set}}{V_{knee}}$ = exciting current of each CT at the relay circuit setting voltage (assuming all CTs are identical)

I_{set} = Relay current setting

I_{var} = current in non linear resistor at the relay circuit setting voltage, calculated with eqn (13)

When relay setting voltage is low and no varistor is required (see section 0), then current in varistor can be ignored.

Maximum Sensitivity

With $I_{set} = I_{set,min}$ (minimum setting current of the protection device), the maximum sensitivity (lowest detectable fault current) can be calculated.

$$I_{p,set,min} = K_n \cdot \left(N_{ct} \cdot I_{e,set} + I_{set,min} + I_{var}\right) \tag{6}$$

Very often, it is given as percent value related to the nominal current of the CTs.

$$Sens_{max} = 100\% \cdot \frac{I_{p,set,min}}{I_{pn}} \tag{7}$$

The current $I_{p,set}$ should fall within the recommended fault setting and be significantly greater than a specified minimum $I_{p,min}$ (where $I_{p,min}$ is an acceptable percentage of the minimum primary fault current $I_{k,min}$). Therefore the relay setting current can be calculated:

$$I_{set} = \frac{I_{p,set}}{K_n} - \cdot N_{ct} \cdot I_{e,set} - I_{var} \tag{8}$$

With this known setting current, the value of the stabilising resistance is calculated with eqn (4).

$$R_{stab} = \frac{V_{set} - V_r}{I_{set}} = \frac{V_{set}}{I_{set}} - R_r \tag{9}$$

where

R_r = relay burden of the used input in Ohm

2.3 Voltage Limiting Resistor

The previous calculations enable the relay voltage setting for through fault stability to be determined, now the case for an internal fault needs to be considered. The maximum primary fault current will cause high voltage spikes across the relay at instants of zero flux since a practical CT core enters saturation on each half-cycle for voltages of this magnitude. If this voltage exceeds 1.5 kV peak then it is necessary to suppress the voltage with a non linear resistor (varistor) in a shunt connection which will pass the excess current as the voltage rises. The formula to calculate this voltage is:

$$\hat{V}_{k,max} = 2 \cdot \sqrt{2 \cdot V_{knee} \cdot \left(V_{k,max,nosat} - V_{knee}\right)} \tag{10}$$

where

$\hat{V}_{k,max}$ = peak value of the voltage waveform

$V_{k,max,nosat}$ = value of voltage that would appear if CT did not saturate

$= \frac{I_{k,max,int}}{K_n} \cdot (R_r + R_{stab})$ where R_r = relay resistance

The varistor must be chosen to match the relay circuit setting voltage (i.e. its characteristic must not change significantly until beyond the relay setting V_{set}) and it must be capable of passing the maximum prospective fault current that can be transformed by the CT.

The type of varistor required is chosen by its thermal rating as defined by the following formula with the varistor parameters in *Table 1*:

$$P_{var} = \frac{I_{k,max,int}}{K_n} \cdot \alpha_u \cdot C \cdot \left(\sqrt{2} \cdot \frac{I_{k,max,int}}{K_n} \right)^{\beta} \qquad (11)$$

The absorbed thermal energy during short-circuit current flow is

$$E_{var} = P_{var} \cdot t_k \qquad (12)$$

User must determine the required duration of fault t_k (0.5 seconds is an accepted value) and calculate the rating using eqn (12) result and 0.5 s.

There are 2 main types of varistors available from Metrosil which can be chosen appropriate to these values.

Metrosil identification	Nominal Characteristic			Max Relay Setting Voltage [V rms]	Recommen-ded Peak Voltage [V]	R. Energy Absorp. For 200°C Temp Rise. [J]	Short Time Current [A rms]		
	C	β	α				1 s	2 s	3 s
600A/S1/S256	450	0.25	0.87	200	1725	53333	45	30	22
600A/S1/S1088	900	0.25	0.87	350	1725	88000	39	23	17

Table 1: Metrosil varistor types (mostly used)

The varistor current at setting voltage is calculated from its characteristics.

$$I_{var} = \left(\sqrt{2} \cdot \frac{V_{set}}{C} \right)^{\beta} \cdot 0.52 \cdot 1000 \text{ in [mA]} \qquad (13)$$

2.4 Thermal Rating of Stabilising Resistor

The resistors incorporate in the scheme must be capable of withstanding the associated thermal conditions.

2.4.1 Continuous Power Rating

The continuous power rating of a resistor is defined as:

$$P_{cont,stab} = I_{set}^2 R_{stab} \qquad (14)$$

where

$P_{cont,stab}$ = resistor continuous power rating

I_{set} = continuous resistor current i.e. the setting current of the relay

R_{stab} = stabilising resistance

2.4.2 Short-Time Power Rating

The rms voltage developed across a resistor for maximum internal fault conditions is defined as:

$$V_{k,max} = 1.3 \cdot \sqrt[4]{V_{knee}^3 \cdot R_{stab} \cdot \frac{I_{k,max,int}}{K_n}} \tag{15}$$

where

$V_{k,max}$ = rms voltage across resistor

$I_{k,max,int}$ = maximum internal fault current

Thus the short-time power rating is given by:

$$E_{st,stab} = P_{st,stab} \cdot t_k = \frac{V_{k,max}^2}{R_{stab}} \cdot t_k \tag{16}$$

where

$P_{st,stab}$ = half-second power rating

t_k = time of short-circuit current flow

3 Connection Example

Figure 1 shows the connection example for an object with two ends protected by one overcurrent protection device 7SJ602 with three phase current inputs. This is the normal case when the minimum phase setting current of 0.1 A is sufficient for the desired sensitivity.

If a higher sensitivity (lower setting current) is needed, then the earth current inputs I_E (0.05-25 A) or sensitive earth current inputs I_{EE} (0.003-1.5 A) can be used. In this case three protection devices with one earth current input of each are needed. This case is shown in Figure 2.

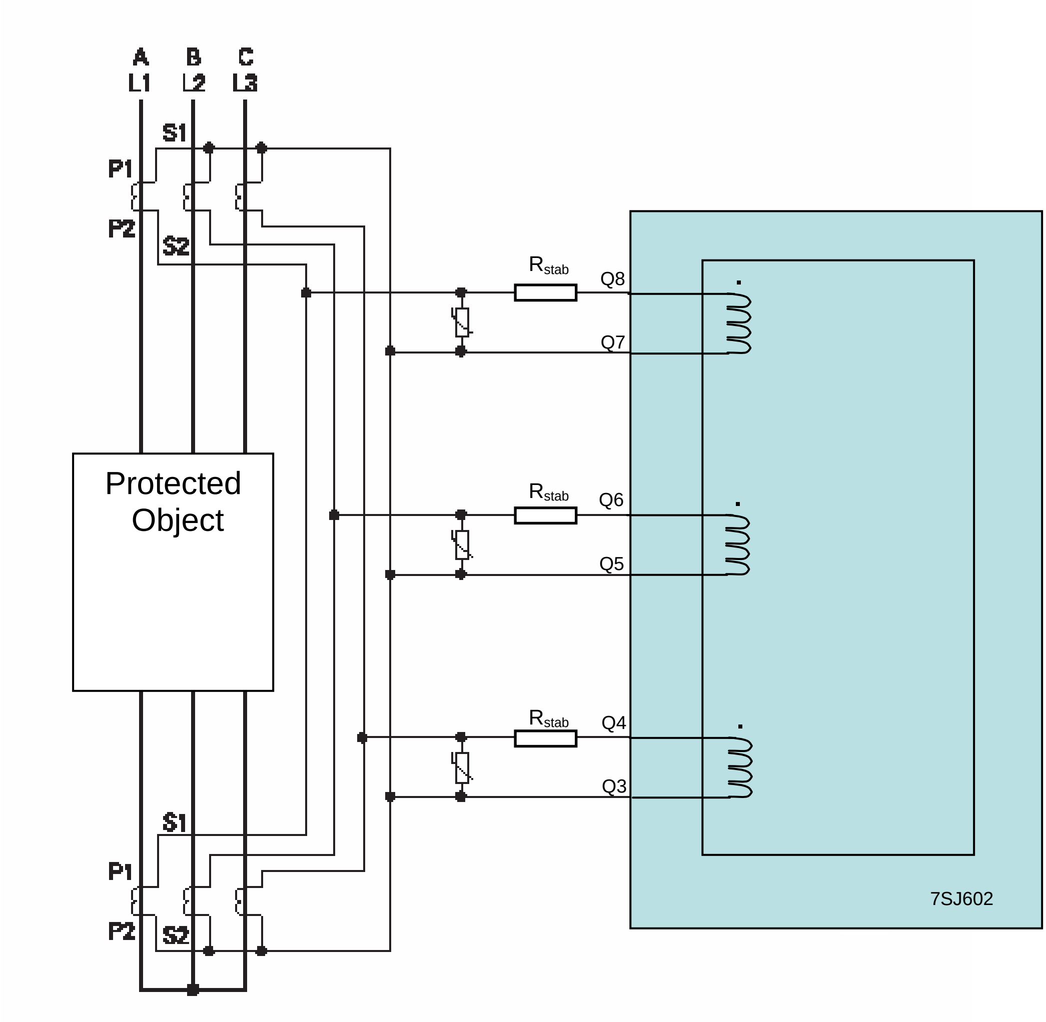

Figure 1: Connection Example

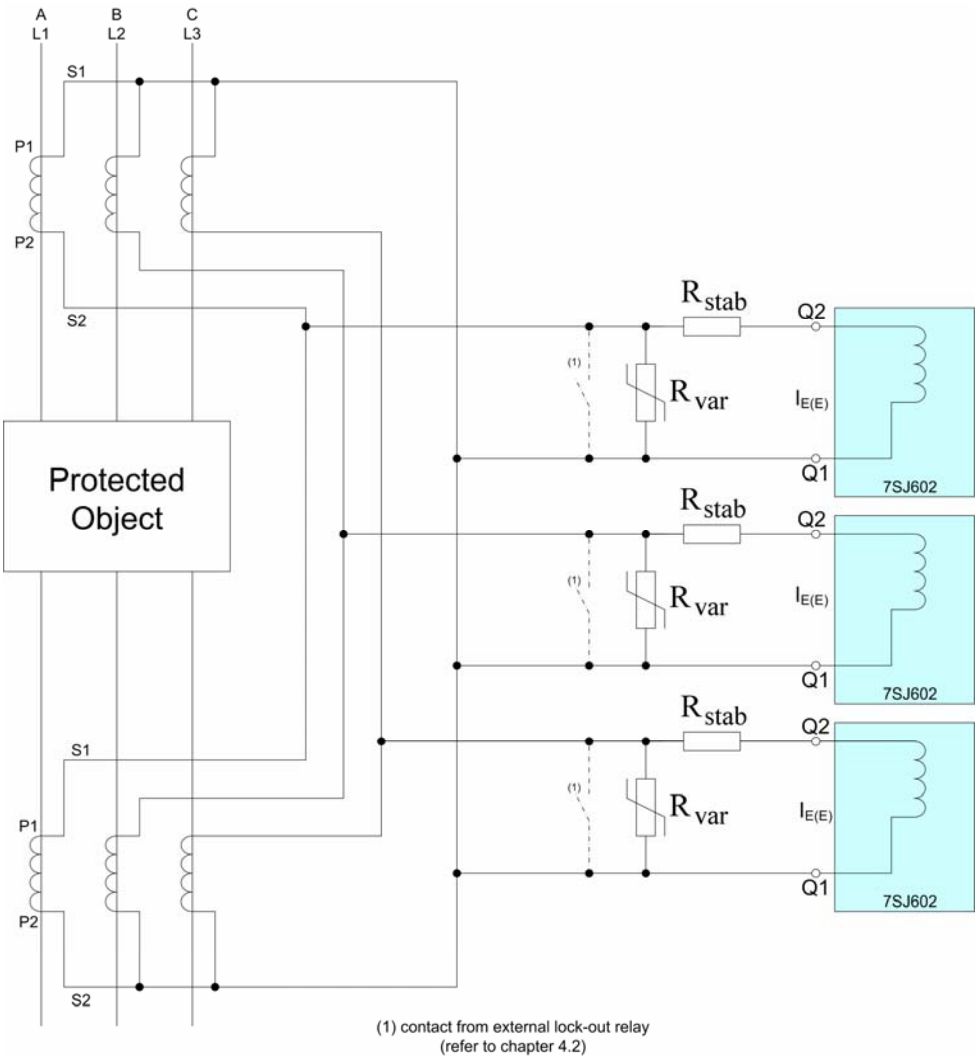

Figure 2: Connection example for three protection devices where the earth current inputs are used.

4 Worked Example

The following worked example shows the application of a high impedance bus bar protection including CT supervision. The bus bar contains 10 items (incomers and feeders) in total.

4.1 Data

4.1.1 System Information

a) Maximum through fault current for external faults $I_{k,max,thr} = 40\,kA$

b) Maximum internal fault current $I_{k,max,int} = 40\,kA$

c) Minimum internal fault current $I_{k,min,int} = 40\,kA$ (solid earthed, assumed)

d) Lowest nominal feeder load current $I_{n,min,load} = 1000\,A$

4.1.2 Current Transformer Information

The CTs are low leakage reactance type having an accuracy class PX in accordance with IEC.

a) Turns ratio $K_n = \frac{I_{pn}}{I_{sn}} = \frac{2500\,A}{1\,A} = 2500$

b) Secondary resistance $R_{ct} = 5\Omega$

c) Knee-point voltage $V_{knee} = 300\,V$
Magnetising current at knee-point voltage $I_{knee} = 10\,mA$

d) CT lead loop resistance $R_L = 1\Omega$

4.1.3 Protection Relay Information (7SJ602)

a) Operating current or current setting range of AC inputs 1 A nominal
3 phases: $I_{set} = 0.1..25\,A(\text{steps}\,0.1)$
1 earth: $I_{set} = 0.05..25\,A\,(\text{steps}\,0.01)$
1 earth (sensitive): $I_{set} = 0.003..1.5\,A\,(\text{steps}\,0.001)$

b) Operating ohmic relay burden
$R_r = 0.1\Omega$ for 3-phase and earth inputs at 1 A nominal.
$R_r = 0.05\Omega$ for sensitive earth input at 1 A nominal.

4.2 Fault Setting

4.2.1 Relay Setting Voltage

From eqn (2) with the given through fault current

$$V_{set} \geq \frac{I_{k,max,thr}}{K_n}\left(R_{ct} + R_L\right) = \frac{40\,kA}{2500}(5+1)\Omega = 96\,V$$

Set V_{set} to 100 V

From eqn (3) the knee point voltage is satified.

$$\frac{V_{knee}}{2} = \frac{300\,V}{2} = 150\,V \geq V_{set} = 100\,V \quad (17)$$

Thus to maintain stability for maximum through fault current the relay needs to be set at a voltage in the range 100V to 150 V.

4.2.2 Relay Setting Current

Maximum Sensitivity

The minimum primary operating current (maximum sensitivity) may be calculated using the practical approximation:

$$I_{p,set,min} = K_n \cdot \left(N_{ct} \cdot I_{e,set} + I_{set,min} + I_{var}\right) \qquad (18)$$

where

$I_{p,set}$	334 or 208 or 91.6 A, depending on the used inputs of 7SJ602 (see below)
N_{ct}	10
$I_{e,set}$	$= I_{knee} \frac{V_{set}}{V_{knee}}$
$I_{set,min}$	0.1 A or 0.05 or 0.003 A, depending on the used inputs of 7SJ602
I_{var}	0.32 mA at setting voltage, determined from eqn (13)

The maximum sensitivity is therefore

$Sens_{max}$	13.3% or 8.3% or 3.6%, depending on the used inputs of 7SJ602 (see above)

Setting for Internal Faults at Bus Bar

The desired sensitivity for bus par protection against internal faults is assumed to 105%, which corresponds to 2625 A primary current.

$$I_{p,set} = 105\% \cdot I_{pn} = 1.05 \cdot 2500\,A = 2625\,A$$

$$I_{set} = \frac{I_{p,set}}{K_n} - \cdot N_{ct} \cdot I_{e,set} - I_{var} = \frac{2625\,A}{2500\,A} - 10 \cdot 0.01\,A \frac{100\,V}{300\,V} - 0.00032 = 1.016\,A$$

$\rightarrow 1\,A$ (according to the setting steps of the phase inputs)

$\rightarrow 103\%$ sensitivity

For this purpose, relay 7SJ602 is set for tripping

I>>	1 A
t>>	0 sec

With this known setting current, the value of the stabilising resistance is calculated using eqn (4).

$$R_{stab} = \frac{V_{set} - V_r}{I_{set}} = \frac{V_{set}}{I_{set}} - R_r = \frac{100\,V}{1A} - 0.1\Omega \approx 100\,\Omega$$

Setting for CT supervision

With the relay 7SJ602 additional CT supervision can be incorperated. Depending on load flow conditions, it is good practice to set CT supervision to a third (33%) of the minimum nominal load current among all feeders at the bus bar. In this example:

$$I_{p,set} = 0.33 \cdot I_{pn,min} = 0.3 \cdot 1000\,A = 333\,A$$

$$I_{set} = \frac{I_{p,set}}{K_n} - \cdot N_{ct} \cdot I_{e,set} - I_{var} = \frac{333\,A}{2500\,A} - 10 \cdot 0.01\,A \frac{100\,V}{300\,V} - 0.00032\,A = 0.099\,A$$

$\rightarrow 0.1\,A$ (according to the setting steps of the phase inputs)

$\rightarrow 13.3\%$ sensitivity

For this purpose, relay of 7SJ602 is set for alarm only

I>	0.1 A
t>	5 sec

In principal there are several options for further application of the CT supervision alarm. In the worked example this alarm signal will be available after 5 sec based on the timer setting TI> (or TIE>):

1. Alarm only.
2. Route the alarm signal to a binary input of 7SJ602 (annunciation 1721 for I>> or 1724 for IE>>) in order to block the high set element I>> or IE>>.This will avoid a trip of the high impedance busbar protection in case of a through fault under CT broken wire conditions. Please note that this measure will not protect the CT inputs of the relay and the stabilizing resistor against damage under longer lasting through fault conditions.
3. Energize an external lock-out relay with one coil and at least four related contacts (e.g. 7PA23). The lock-out relay has to be energized by the CT supervision alarm signal. One contact should be placed in front of the varistor to short circuit each CT input of 7SJ602. The fourth contact of the lock-out relay is for signaling the ‘high impedance busbar out-of-service’ information. The reset of the external lock-out relay has to be done manually.
   This measure will protect the CT inputs of the relay and the stabilizing resistor against damage under longer lasting through fault conditions.

4.3 Voltage Limiting Resistor

If no saturation would appear in the CTs, the maximum rms voltage due to the maximum internal fault current would be

$$V_{k,max,nosat} = \frac{I_{k,max,int}}{K_n} \cdot (R_r + R_{stab}) = \frac{40\,kA}{2500\,A} \cdot (0.1 + 100)\Omega = 1.6\,kV$$

The maximum peak value of the waveform due to CT saturation from eqn (10) is

$$\hat{V}_{k,max} = 2 \cdot \sqrt{2 \cdot V_{knee} \cdot (V_{k,max,nosat} - V_{knee})}$$

$$= 2 \cdot \sqrt{2 \cdot 300\,V \cdot (1.6\,kV - 300\,V)} = 1.77\,kV$$

As this voltage is higher than 1.5 kV, a **varistor is required**. The thermal losses during a maximum internal fault are calculated with eqn (11).

$$P_{var} = \frac{I_{k,max,int}}{K_n} \cdot \alpha_u \cdot C \cdot \left(\sqrt{2} \cdot \frac{I_{k,max,int}}{K_n} \right)^{\beta}$$

$$= \frac{40kA}{2500} \cdot 0.87 \cdot 900 \cdot \left(\sqrt{2} \cdot \frac{40kA}{2500} \right)^{0.25} = 27.3kW$$

A Metrosil 600A/S1/S1088 is chosen. Acc. to eqn (12) its maximum thermal energy (88 kJ) is not exceeded even for a short-circuit current flow of 3 seconds.

4.4 Thermal Rating of Stabilising Resistor

4.4.1 Continuous Power Rating

The continuous power rating of the stabilising resistor acc. to eqn (14) is calculated:

$$P_{cont,stab} = I_{set}^2 R_{stab} = (1\,A)^2 \cdot 100\,\Omega = 100\,W$$

4.4.2 Short-Time Power Rating

The short-time power rating for 0.5 s of the stabilising resistor acc. to eqns (15) and (16) is

$$V_{k,max} = 1.3 \cdot \sqrt[4]{V_{knee}^3 \cdot R_{stab} \cdot \frac{I_{k,max,int}}{K_n}} = 1.3 \cdot \sqrt[4]{(300\,V)^3 \cdot 100\,\Omega \cdot \frac{40\,kA}{2500}} = 592.7V$$

$$E_{st,stab} = P_{st,stab} \cdot t_k = \frac{V_{k,max}^2}{R_{stab}} \cdot t_k = \frac{(592.7\,V)^2}{100\,\Omega} \cdot 0.5s = 1756.3J$$