Definitions and Terms for Pulsed Output PEF Generators

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A Standard Set of Definitions and Terms to describe the Pulsed Output of PEF Generators

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Abstract

This paper contains definitions for terms that are necessary for understanding the pulsed output of pulsed-electric-field (PEF) generators. Defined terms are printed in SMALL CAPITAL to assist the reader in identifying them throughout the document. When normal case is used, the words have their normal English meaning.

Keywords: Pulsed Electric Field, Terms, Definitions, Pulsed Output, Accuracy, Distortion

1 General Terms

1.1 Coordinate System

Throughout this document a rectangular Cartesian coordinate system is assumed, where unless otherwise specified;

(1) TIME (t) is the independent variable taken along the horizontal axis, increasing in the positive sense from left to right.

(2) MAGNITUDE (y) is the dependant variable taken along the vertical axis increasing in the positive sense of polarity from bottom to top which represents the size or amount of a quantity. The quantity may be voltage v, current i, power p, energy e, system input signal u, reference signal r, system output signal y etc.

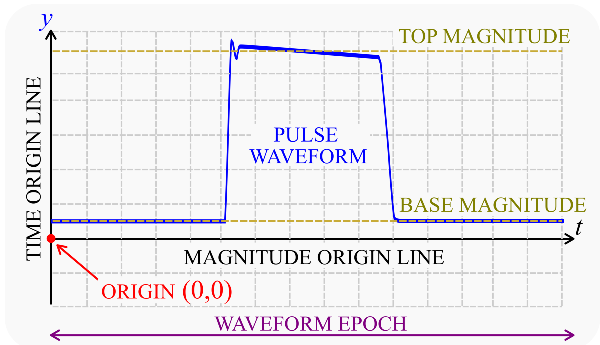

Fig. 1: A PULSE WAVEFORM with MAGNITUDE y depicted across TIME t on a rectangular coordinate system.

1.2 Time Origin Line

The TIME ORIGIN LINE is a line of constant and specified TIME which unless otherwise specified has a TIME equal to zero at the first data point of a WAVEFORM EPOCH. (See Fig. 1.)

1.3 Magnitude Origin Line

The MAGNITUDE ORIGIN LINE is a line with constant MAGNITUDE equal to zero which extends though the WAVEFORM EPOCH. (See Fig. 1.)

1.4 Origin

The ORIGIN is the intersecting point bewteen the TIME ORIGIN LINE and the MAGNITUDE ORIGIN LINE which occurs at the point $(t, y) = (0, 0)$. (See Fig. 1.)

1.5 Pulse

A PULSE is a rapid change in the MAGNITUDE of a quantity from a BASE MAGNITUDE to a TOP MAGNITUDE followed by a rapid return to the BASE MAGNITUDE. (See Fig. 1.)

1.6 Waveform

A WAVEFORM is a graphical representation of how a quantity changes as a function of TIME t. (See Fig. 1.)

1.7 Epoch

The EPOCH of a WAVEFORM is the span of time for which the WAVEFORM data are known or knowable. (See Fig. 1.)

1.8 Instant

An INSTANT is a specific moment in time specified with respect to the ORIGIN data point of a WAVEFORM EPOCH.

1.9 Interval

An INTERVAL is a convex subset of TIME defined between a first INSTANT and a second INSTANT.

1.10 Accuracy

ACCURACY σ is defined as the algebraic difference between a measured quantity and its true value. Or, ACCURACY σ can also be defined as the algebraic difference between the desired value of a quantity and its true value.

2 Single-Pulse Waveform-Related Definitions

2.1 Proximal Line

The PROXIMAL LINE is a line of constant MAGNITUDE of $Y_B + \frac{1}{10}Y$, where Y is the PULSE AMPLITUDE and Y_B is the BASE MAGNITUDE of the PULSE WAVEFORM. (See Fig. 2.)

2.2 Mesial Line

The MESIAL LINE is a line of constant MAGNITUDE of $Y_B + \frac{1}{2}Y$, where Y is the PULSE AMPLITUDE and Y_B is the BASE MAGNITUDE of the PULSE WAVEFORM. (See Fig. 2.)

2.3 Distal Line

The DISTAL LINE is a line of constant MAGNITUDE of $Y_B + \frac{9}{10}Y$, where Y is the PULSE AMPLITUDE and Y_B is the BASE MAGNITUDE of the PULSE WAVEFORM. (See Fig. 2.)

2.4 Pulse Start

The PULSE START is the INSTANT at which the PULSE MAGNITUDE first crosses the MESIAL LINE. (See Fig. 2.)

2.5 Pulse Stop

The PULSE STOP is the INSTANT at which the PULSE MAGNITUDE last crosses the MESIAL LINE. (See Fig. 2.)

2.6 Pulse Midpoint

The PULSE MIDPOINT is the INSTANT which is equi-distant from the PULSE START and PULSE STOP. (See Fig. 2.)

2.7 First Transition

The FIRST TRANSITION is the INTERVAL between the INSTANT where the PULSE MAGNITUDE first crosses the PROXIMAL LINE and first crosses the DISTAL LINE. (See Fig. 2.)

2.8 Last Transition

The LAST TRANSITION is the INTERVAL between the INSTANT where the PULSE MAGNITUDE last crosses the DISTAL LINE and last crosses the PROXIMAL LINE. (See Fig. 2.)

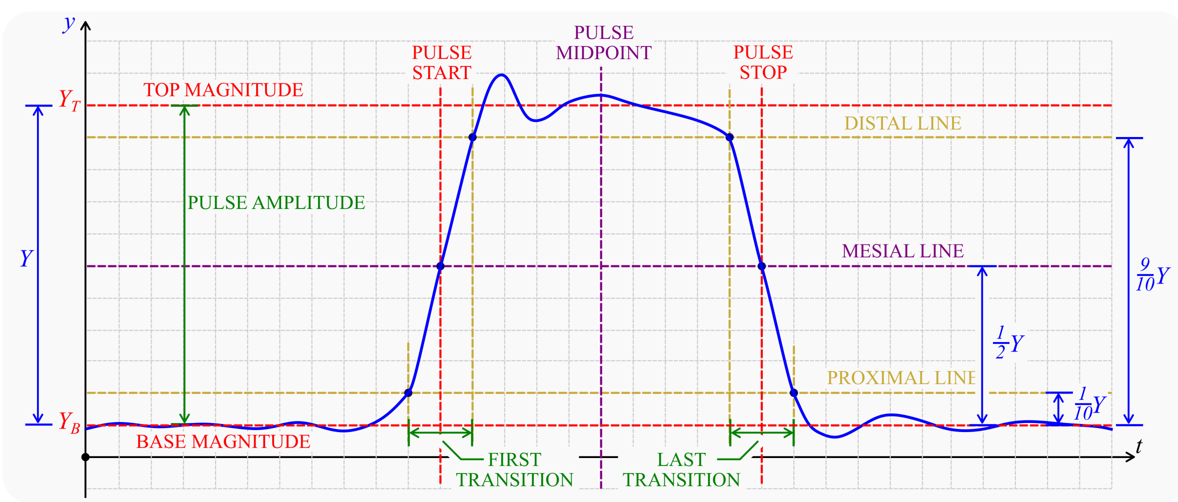

Fig. 2: A single pulse.

2.9 Reference

REFERENCE is an adjective use to describe a WAVEFORM, PULSE or parameter which is used for the purpose of comparison to a measured WAVEFORM, PULSE or parameter. The REFERENCE WAVEFORM is commonly notated $r(t)$.

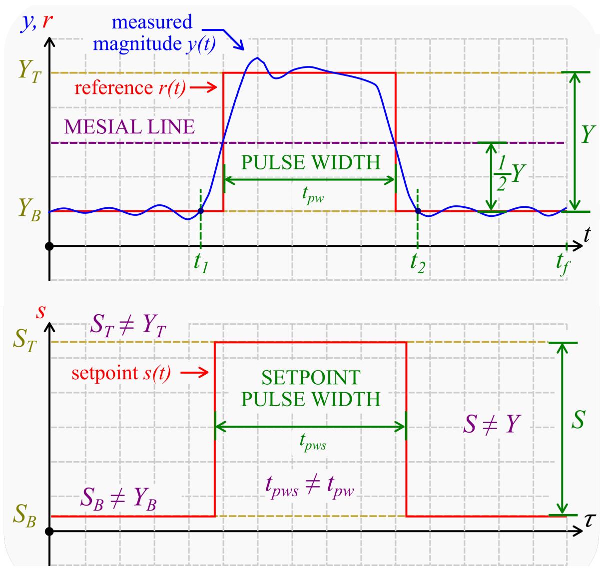

Fig. 3: The REFERENCE WAVEFORM $r(t)$ and SETPOINT WAVEFORM $s(\tau)$ of a RECTANGULAR PULSE with MAGNITUDE $y(t)$.

2.10 Rectangular Pulse

A RECTANGULAR PULSE is a pulse waveform which has a shape approaching that of a rectangle. The REFERENCE WAVEFORM of a RECTANGULAR PULSE has a constant MAGNITUDE equal to the BASE MAGNITUDE before the FIRST TRANSITION and after the LAST TRANSITION and a constant MAGNITUDE equal to the TOP MAGNITUDE during the INTERVAL between the FIRST and LAST TRANSITIONS. The TIME duration of the FIRST TRANSITION and LAST TRANSITION is zero. (See Fig. 3.)

2.11 Setpoint

SETPOINT is an adjective use to describe a WAVEFORM, PULSE or parameter which describes the desired MAGNITUDE of a given quantity. The SETPOINT WAVEFORM is commonly notated $s(\tau)$ and has the same shape as the REFERENCE WAVEFORM $r(t)$ but has a different MAGNITUDE as depicted in Fig. 3 for a RECTANGULAR PULSE. In this case, the SETPOINT PULSE AMPLITUDE S is the desired PULSE AMPLITUDE of the PULSE $y(t)$. Similarly, the SETPOINT PULSE WIDTH t_{pws} is the desired PULSE WIDTH of the PULSE $y(t)$. The SETPOINT WAVEFORM $s(\tau)$ is defined along a separate TIME axis notated τ where $\tau = t - \tau_d$, where τ_d is a fixed delay.

2.12 Pulse Power

The PULSE POWER p is the power transferred by a single PULSE. If a PULSE voltage is described by a WAVEFORM $v(t)$ and a current WAVEFORM $i(t)$ the pulse power can be found as

$$p(t) = i(t)v(t) \tag{1}$$

2.13 Pulse Energy

The PULSE ENERGY E is defined as the energy delivered by a PULSE during the interval from t_1 to t_2. If a PULSE voltage is described by a WAVEFORM $v(t)$ and a current WAVEFORM $i(t)$ the pulse power can be found as

$$E = \int_{t=t_1}^{t_2} i(t)v(t)\mathrm{d}t \tag{2}$$

where,

- t_1 is the last INSTANT before the FIRST TRANSITION when the PULSE MAGNITUDE $y(t)$ crosses the REFERENCE MAGNITUDE $r(t)$
- t_2 is the first INSTANT after the LAST TRANSITION when the PULSE MAGNITUDE $y(t)$ crosses the REFERENCE MAGNITUDE $r(t)$

2.14 Pulse Train

A PULSE TRAIN is defined as a continuous repetitive sequence of PULSES. (See Fig. 4.)

2.15 Unipolar

UNIPOLAR is an adjective used to describe a WAVEFORM which has a MAGNITUDE of only a single polarity during the WAVEFORM EPOCH. The polarity may be positive or negative. (See Fig. 4.)

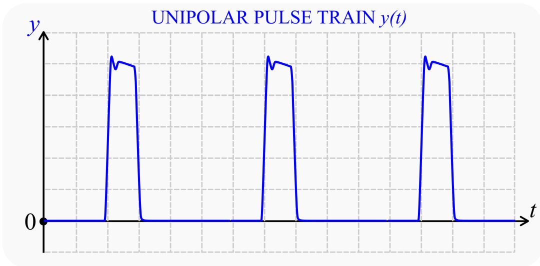

Fig. 4: A UNIPOLAR PULSE TRAIN.

2.16 Bipolar

BIPOLAR is an adjective used to describe a WAVEFORM which has a MAGNITUDE which is both positive and negative during the WAVEFORM EPOCH.

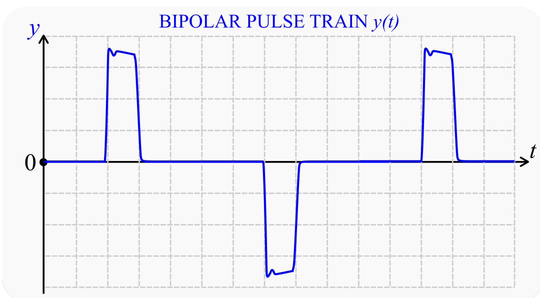

Fig. 5: A BIPOLAR PULSE TRAIN.

3 Single-Pulse Magnitude-Related Definitions

3.1 Base Magnitude

The BASE MAGNITUDE of a PULSE $y(t)$ is defined as the MAGNITUDE Y_B which satisfies the integral equation (3).

$$Y_B = \frac{1}{t_1 + (t_f - t_2)} \left(\int_{t=0}^{t_1} y(t)\mathrm{d}t + \int_{t=t_2}^{t_f} y(t)\mathrm{d}t \right) \tag{3}$$

where,

t_1 is the last INSTANT before the FIRST TRANSITION when the PULSE MAGNITUDE $y(t)$ crosses the REFERENCE MAGNITUDE $r(t)$

t_2 is the first INSTANT after the LAST TRANSITION when the PULSE MAGNITUDE $y(t)$ crosses the REFERENCE MAGNITUDE $r(t)$

t_f is the INSTANT of the last data point in the WAVEFORM EPOCH

(See Fig. 3.)

3.2 Top Magnitude

The TOP MAGNITUDE of a PULSE $y(t)$ is defined as the MAGNITUDE Y_T which satisfies the following integral equation (4).

$$\int_{t=t_1}^{t_2} (y(t) - Y_B)\mathrm{d}t = \int_{t=t_1}^{t_2} (r(t) - Y_B)\mathrm{d}t \tag{4}$$

where,

$r(t)$ is the REFERENCE MAGNITUDE

t_1 is the last INSTANT before the FIRST TRANSITION when the PULSE MAGNITUDE $y(t)$ crosses the REFERENCE MAGNITUDE $r(t)$

t_2 is the first INSTANT after the LAST TRANSITION when the PULSE MAGNITUDE $y(t)$ crosses the REFERENCE MAGNITUDE $r(t)$

(See Fig. 3.)

3.3 Pulse Amplitude

The PULSE AMPLITUDE Y is defined as the algebraic difference between the TOP MAGNITUDE and BASE MAGNITUDE of a PULSE. (See Fig. 3.)

3.4 Maximum Pulse Magnitude

The MAXIMUM PULSE MAGNITUDE Y_{max} is defined as the maximum MAGNITUDE of a PULSE $y(t)$ during the WAVEFORM EPOCH.(See Fig. 6.)

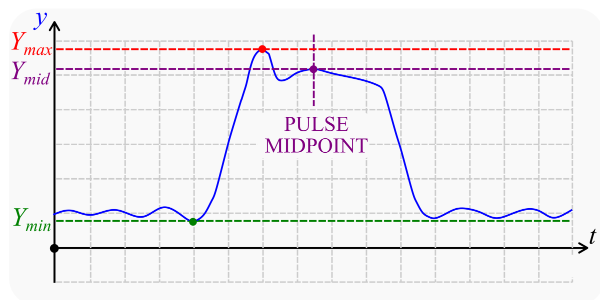

Fig. 6: The MAXIMUM, MINIMUM and MIDPOINT MAGNITUDES of a PULSE $y(t)$.

3.5 Minimum Pulse Magnitude

The MINIMUM PULSE MAGNITUDE Y_{min} is defined as the minimum MAGNITUDE of a PULSE $y(t)$ during the WAVEFORM EPOCH.(See Fig. 6.)

3.6 Midpoint Pulse Magnitude

The MIDPOINT PULSE MAGNITUDE Y_{mid} is defined as the MAGNITUDE of a PULSE $y(t)$ at the PULSE MIDPOINT.(See Fig. 6.)

3.7 Pulse Amplitude Accuracy

The PULSE AMPLITUDE ACCURACY σ_Y is the defined as the algebraic difference between the PULSE AMPLITUDE of a PULSE and the PULSE AMPLITUDE of it's SETPOINT PULSE. Unless otherwise stated PULSE AMPLITUDE ACCURACY is expressed as a percentage of the SETPOINT PULSE AMPLITUDE.

$$\sigma_Y = \frac{S - Y}{S} \times 100\% \tag{5}$$

3.8 Pulse Distortion

The PULSE DISTORTION $d(t)$ is the algebraic difference between the MAGNITUDE of the PULSE and the MAGNITUDE of the REFERENCE waveform as depicted in Fig. 7

3.9 Overshoot

The OVERSHOOT is defined as the maximum DISTORTION during the interval between the PULSE START and the PULSE STOP.

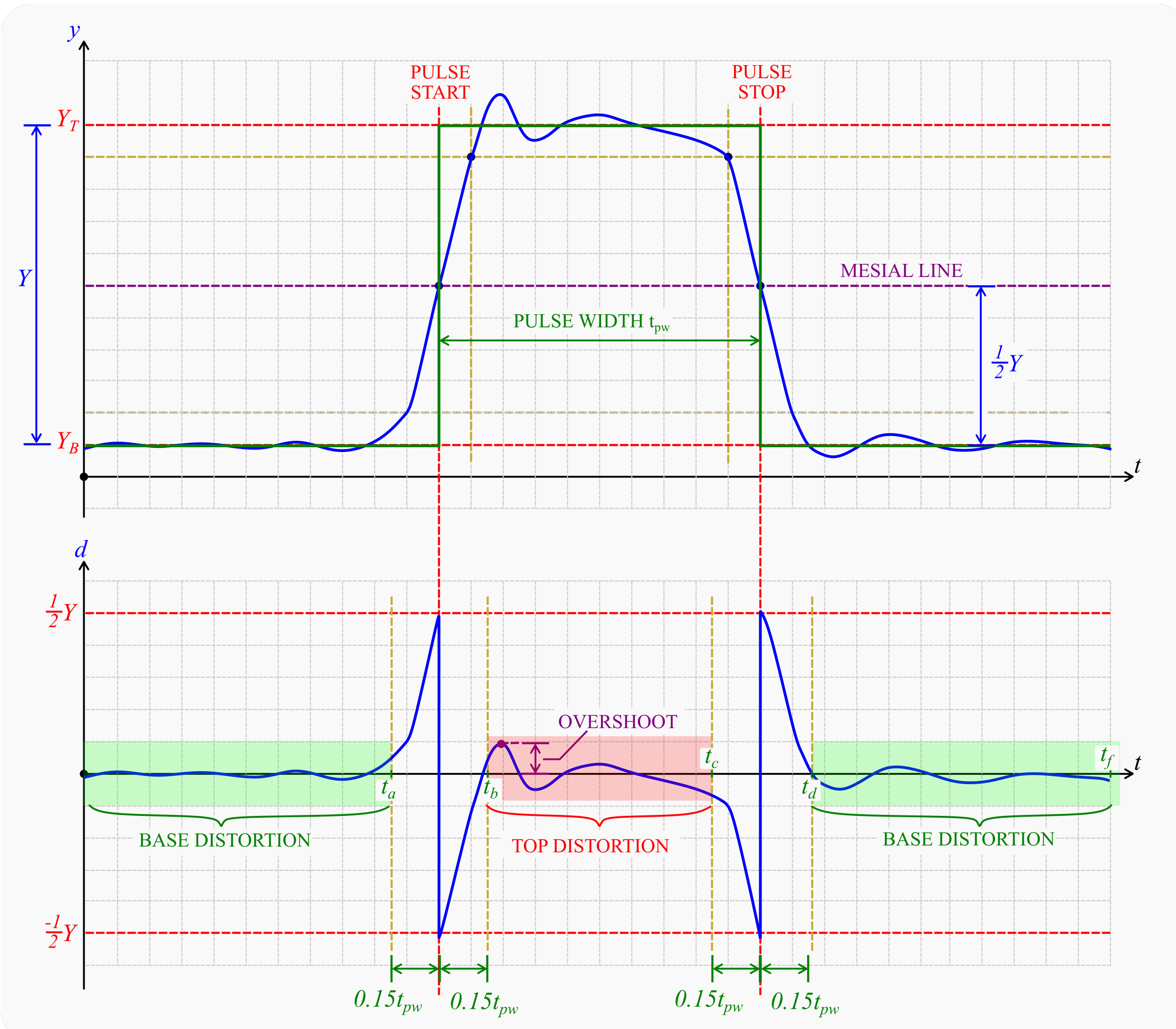

Fig. 7: Pulse distortion $d(t)$.

3.10 Top Distortion

The TOP DISTORTION $d_t(t)$ is defined as the PULSE DISTORTION $d(t)$ during the INTERVAL $t_b \leq t \leq< t_c$ such that,

$$\begin{aligned} d_t(d) &= \text{null} && \text{for} \quad 0 \leq t < t_b \\ d_t(d) &= d(t) && \text{for} \quad t_b \leq t < t_c \\ d_t(d) &= \text{null} && \text{for} \quad t_c \leq t < t_f \end{aligned}$$

where,

t_b is the INSTANT which occurs at $0.15t_{pw}$ after the PULSE START

t_c is the INSTANT which occurs at $0.15t_{pw}$ before the PULSE STOP

t_f is the INSTANT of the final data point in the WAVEFORM EPOCH

t_{pw} is the PULSE WIDTH

(See Fig. 7.)

3.11 Base Distortion

The BASE DISTORTION $d_b(t)$ is defined as the PULSE DISTORTION $d(t)$ during the INTERVALS $0 \leq t \leq< t_a$ and $t_d \leq t \leq< t_f$ such that,

$$\begin{aligned} d_b(d) &= d(t) && \text{for} \quad 0 \leq t < t_a \\ d_b(d) &= \text{null} && \text{for} \quad t_a \leq t < t_d \\ d_b(d) &= d(t) && \text{for} \quad t_d \leq t < t_f \end{aligned}$$

where,

t_a is the INSTANT which occurs at $0.15t_{pw}$ before the PULSE START

t_d is the INSTANT which occurs at $0.15t_{pw}$ after the PULSE STOP

t_f is the INSTANT of the final data point in the WAVEFORM EPOCH

t_{pw} is the PULSE WIDTH

(See Fig. 7.)

4 Single-Pulse Time-Related Definitions

4.1 Pulse Width

The PULSE WIDTH is defined as the TIME duration between the PULSE START and the PULSE STOP. (See Fig. 8.)

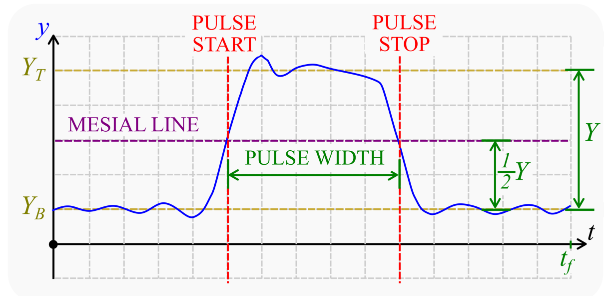

Fig. 8: The PULSE WIDTH of a PULSE $y(t)$.

4.2 Rise Time

The RISE TIME t_r is the defined as the TIME duration between the INSTANTS when the PULSE MAGNITUDE first crosses the PROXIMAL LINE and first crosses the DISTAL LINE as depicted in Fig. 9.

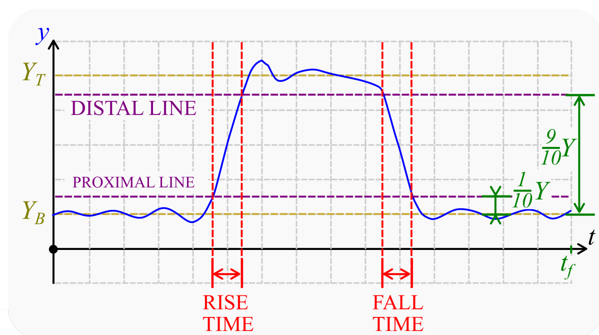

Fig. 9: The RISE TIME t_r and FALL TIME t_f of a PULSE $y(t)$.

4.3 Fall Time

The FALL TIME t_f is the defined as the TIME duration between the INSTANTS when the PULSE MAGNITUDE last crosses the DISTAL LINE and last crosses the PROXIMAL LINE as depicted in Fig. 9.

5 Burst Waveform-Related Definitions

5.1 Burst

A BURST is a finite PULSE TRAIN. (See Fig. 10.)

5.2 Burst Start

The BURST START is the PULSE START of the first PULSE in the BURST. (See Fig. 10.)

5.3 Burst Stop

The BURST STOP is the PULSE STOP of the last PULSE in the BURST. (See Fig. 10.)

5.4 Number of Pulses

The NUMBER OF PULSES N_p is the number of single PULSES within a PULSE TRAIN or BURST. (See Fig. 10.)

5.5 Pulse Index

The PULSE INDEX p refers to the position of a single PULSE within a BURST, such that $p = 1$ refers to the first pulse and $p = N_p$ refers to the last PULSE within the BURST. (See Fig. 10.)

5.6 Unipolar Burst

A UNIPOLAR BURST is a finite PULSE TRAIN of N_p single PULSES which all have a MAGNITUDE of the same polarity. Unless otherwise stated it is assumed all PULSES have a uniform SETPOINT PULSE AMPLITUDE, PULSE WIDTH and PULSE PERIOD. (See Fig. 10.)

5.7 Symmetric Bipolar Burst

A SYMMETRIC BIPOLAR BURST is a finite PULSE TRAIN of N_p single PULSES, where each successive pulse has a pulse amplitude of opposite polarity. Unless otherwise stated it is assumed all PULSES have a uniform absolute value of the SETPOINT PULSE AMPLITUDE and a uniform value of PULSE WIDTH and PULSE PERIOD. (See Fig. 11.)

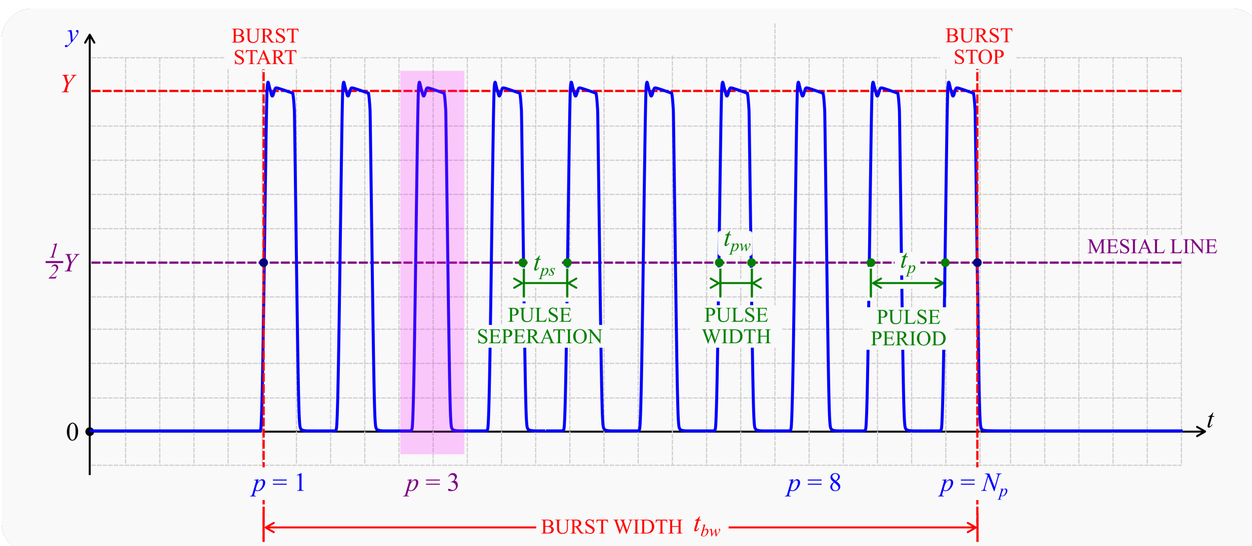

Fig. 10: A single UNIPOLAR BURST $y(t)$.

5.8 Asymmetric Bipolar Burst

An ASYMMETRIC BIPOLAR BURST is a finite PULSE TRAIN of N_p single PULSES, where each successive pulse has a pulse amplitude of opposite polarity, and positive and negative PULSES have different PULSE WIDTHS. Unless otherwise stated it is assumed all PULSES have a uniform absolute value of the SETPOINT PULSE AMPLITUDE and a uniform value of PULSE PERIOD. Positive PULSES have a uniform PULSE WIDTH t_{ppw}, while negative pulses have a uniform NEGATIVE PULSE WIDTH t_{npw}. (See Fig. 12.)

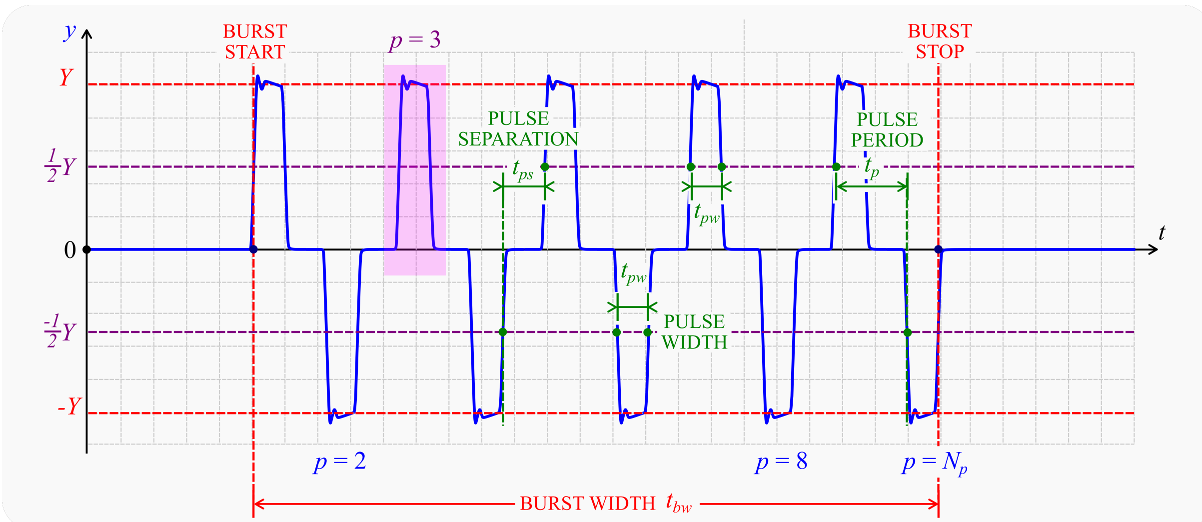

Fig. 11: A single SYMMETRIC BIPOLAR BURST $y(t)$.

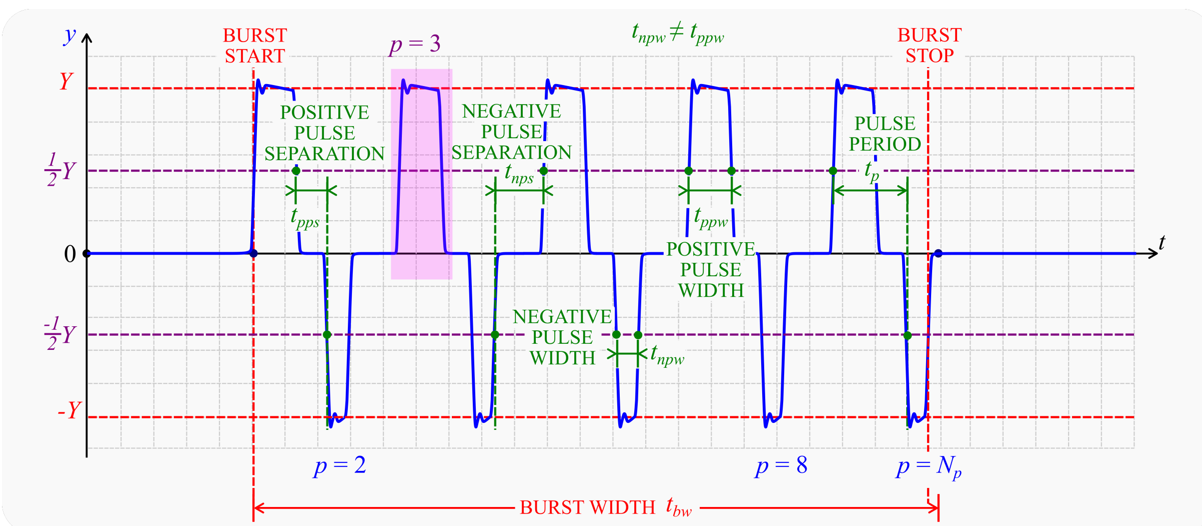

Fig. 12: A single ASYMMETRIC BIPOLAR BURST $y(t)$.

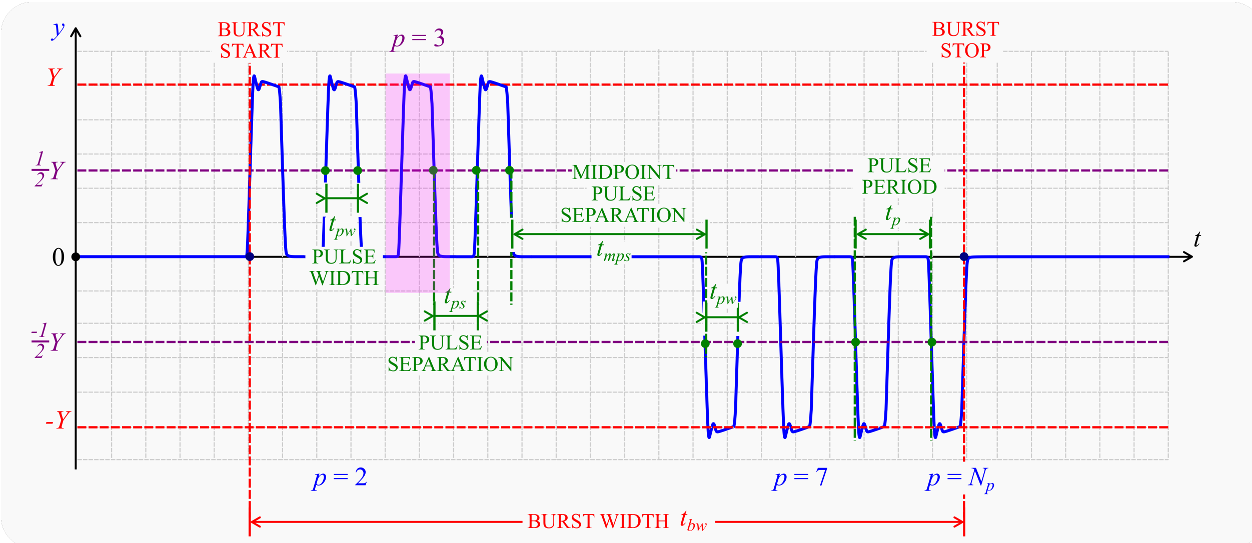

Fig. 13: A single SWITCHED BIPOLAR BURST $y(t)$.

5.9 Switched Bipolar Burst

A SWITCHED BIPOLAR BURST is a finite PULSE TRAIN of N_p single PULSES with a total of N_{pp} pulses with positive polarity and N_{np} with negative polarity. The first N_{pp} pulses all have positive polarity, while the remaining $N_{np} = N_p - N_{pp}$ all have a negative polarity. Unless otherwise stated it is assumed all PULSES have a uniform absolute value of the SET-POINT PULSE AMPLITUDE and a uniform value of PULSE WIDTH and PULSE PERIOD. (See Fig. 13.)

5.10 Burst Train

A BURST TRAIN is defined as a continuous repetitive sequence of BURSTS. (See Fig. 14.)

5.11 Number of Bursts

The NUMBER OF BURSTS N_b is the number of single BURSTS within a BURST TRAIN. (See Fig. 14.)

5.12 Burst Index

The BURST INDEX b refers to the position of a single BURST within a BURST TRAIN, such that $b = 1$ refers to the first burst and $b = N_b$ refers to the last BURST within the BURST TRAIN. (See Fig. 14.)

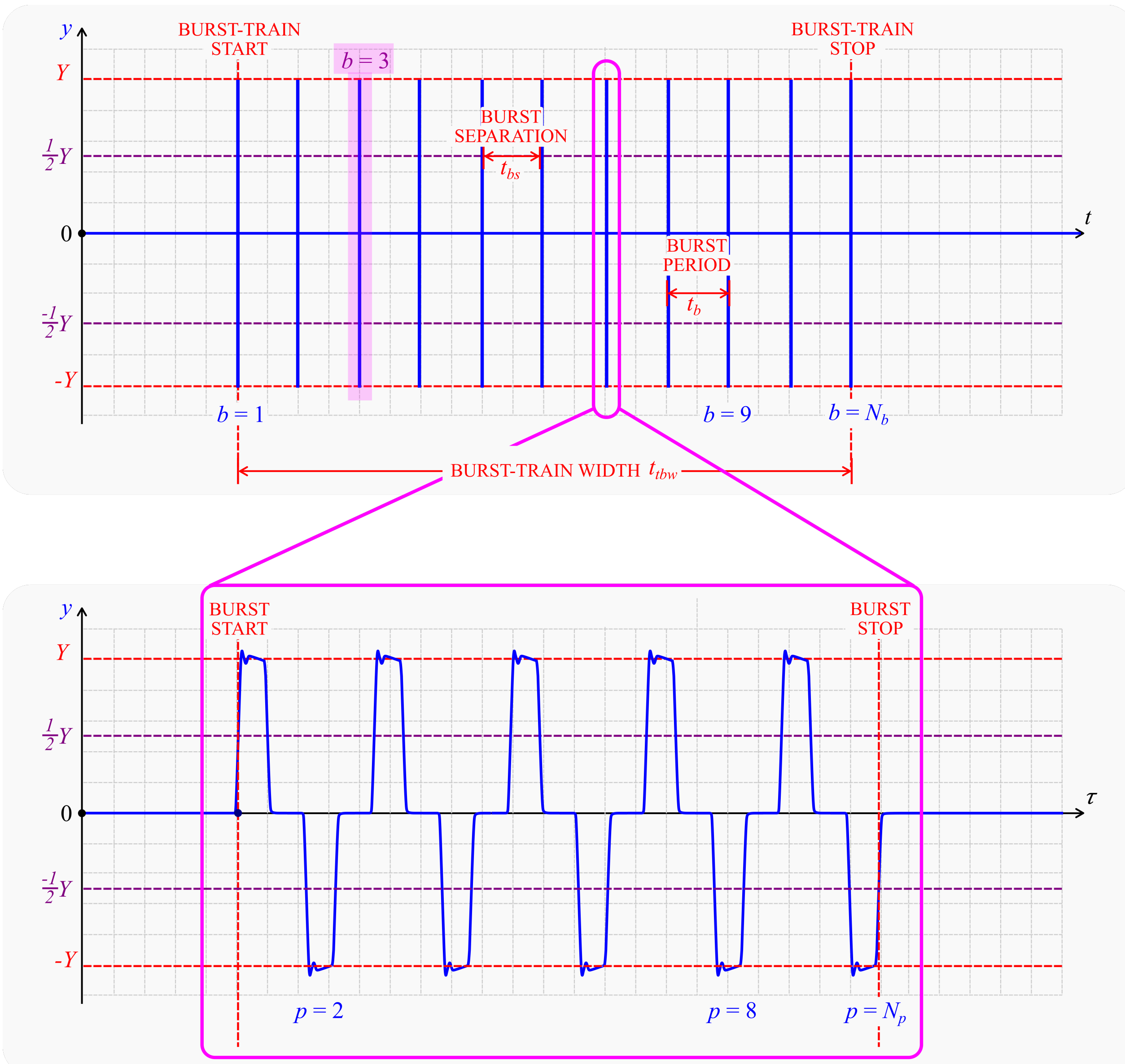

Fig. 14: A single BIPOLAR BURST TRAIN $y(t)$.

6 Burst Time-Related Definitions

6.1 Pulse Period

The PULSE PERIOD t_p is the duration of TIME between the PULSE START of a PULSE within a PULSE TRAIN and the next PULSE with identical features. (See Fig. 10.)

6.2 Positive Pulse Width

The POSITIVE PULSE WIDTH is defined as the TIME duration between the PULSE START and the PULSE STOP of a single PULSE with a positive PULSE AMPLITUDE. (See Fig. 12.)

6.3 Negative Pulse Width

The NEGATIVE PULSE WIDTH is defined as the TIME duration between the PULSE START and the PULSE STOP of a single PULSE with a negative PULSE AMPLITUDE. (See Fig. 12.)

6.4 Pulse Frequency

The PULSE FREQUENCY f_p is the reciprocal of the PULSE PERIOD.

6.5 Pulse Separation

The PULSE SEPARATION t_{ps} is defined as the TIME duration between the PULSE STOP of a PULSE and the PULSE START of the following PULSE within a PULSE TRAIN. (See Fig. 10.)

6.6 Positive Pulse Separation

The POSITIVE PULSE SEPARATION t_{pps} is defined as the TIME duration between the PULSE STOP of a positive PULSE and the PULSE START of the following PULSE within a PULSE TRAIN. (See Fig. 12.)

6.7 Negative Pulse Separation

The NEGATIVE PULSE SEPARATION t_{nps} is defined as the TIME duration between the PULSE STOP of a negative PULSE and the PULSE START of the following PULSE within a PULSE TRAIN. (See Fig. 12.)

6.8 Burst Period

The BURST PERIOD t_b is the duration of TIME between the BURST START of a BURST within a BURST TRAIN and the next BURST START of the next BURST with identical features. (See Fig. 14.)

6.9 Burst Frequency

The BURST FREQUENCY f_b is the reciprocal of the BURST PERIOD.

6.10 Burst Width

The BURST WIDTH $t_b w$ is the duration of TIME between the BURST START and BURST STOP of a BURST. (See Fig. 14.)

6.11 Summated Pulse Width

The SUMMATED PULSE WIDTH t_{spw} is the summation of the PULSE WITH of each single PULSE within a burst.

$$t_{spw} = \sum_{p=1}^{N_p} t_{pw} \tag{6}$$

For a BURST with uniform PULSE WIDTH, the SUMMATED PULSE WIDTH may be calculated by

$$t_{spw} = N_p t_{pw} \tag{7}$$

6.12 Burst Separation

The BURST SEPARATION t_{bs} is defined as the TIME duration between the BURST STOP of a BURST and the BURST START of the following BURST within the BURST TRAIN. (See Fig. 14.)

6.13 Burst-Train Width

The BURST-TRAIN WIDTH t_{btw} is defined as the TIME duration between the BURST START of the first BURST within a BURST TRAIN and the BURST STOP of the last BURST within the BURST TRAIN. (See Fig. 14.)

7 Burst Magnitude-Related Definitions

7.1 Mean Midpoint Pulse Magnitude

The MEAN MIDPOINT PULSE MAGNITUDE Y_{Bmid} is defined as the mean value of the absolute MIDPOINT MAGNITUDES of all PULSES within a BURST. (See Fig. 15.)

$$Y_{Bmid} = \sum_{p=1}^{N_p} \frac{|Y_{pmid}|}{N_p} \tag{8}$$

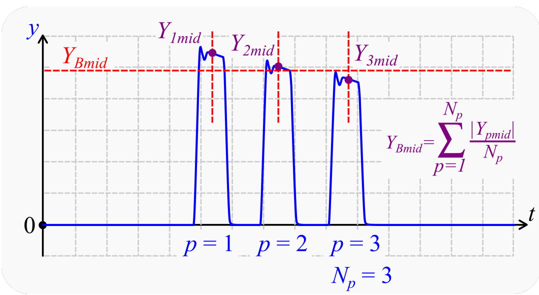

Fig. 15: The MEAN MIDPOINT PULSE MAGNITUDE.

7.2 Mean Pulse Amplitude

The MEAN PULSE AMPLITUDE Y_{Bmean} is defined as the mean value of the absolute PULSE AMPLITUDE of all PULSES within a BURST. (See Fig. 16.)

$$Y_{Bmean} = \sum_{p=1}^{N_p} \frac{|Y_p|}{N_p} \tag{9}$$

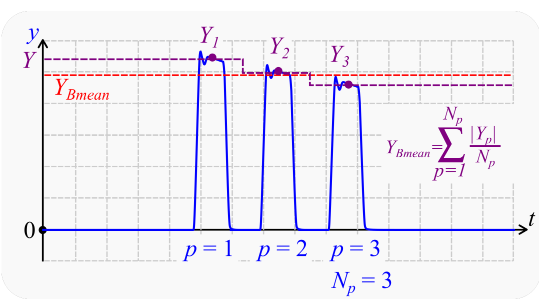

Fig. 16: The MEAN PULSE AMPLITUDE.