Transient detection and classification in energy meters

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Abstract

Power quality tariffs/ incentives provide an impetus to increased discipline in the emerging deregulated power network scenario. Periodic deviations from desired voltage and currents are measured by line frequency deviation, power factor and harmonics (magnitude and phases) while non-periodic deviations are measured by counting specified transients on the line voltages (such as voltage sag, voltage swell, momentary interruption and oscillatory transients). We propose to use the recursive least square algorithm (RLS) to detect, classify and log these transients, allowing transient logging with far less memory than a waveform capture approach (this reduces non-volatile RAM costs in energy meters). We also discuss implementation issues (computational complexity and fixed-point realization) for a DSP-based tariff meter.

1. Introduction

Non-networked energy meters place a premium on non-volatile RAM, while networked energy meters place a premium on communications bandwidth. Thus, detection, classification and logging of power line transients within a meter, reduces demands in either case. This is because only parameters associated with the classified waveform need to be stored/ transmitted (as opposed to a bandwidth-consuming waveform capture). Specified transients (those we desire to control the frequency of) are: Sags, Swells, Oscillatory transients and Momentary interruptions. These events are defined in [1] and depicted in Fig. 1.

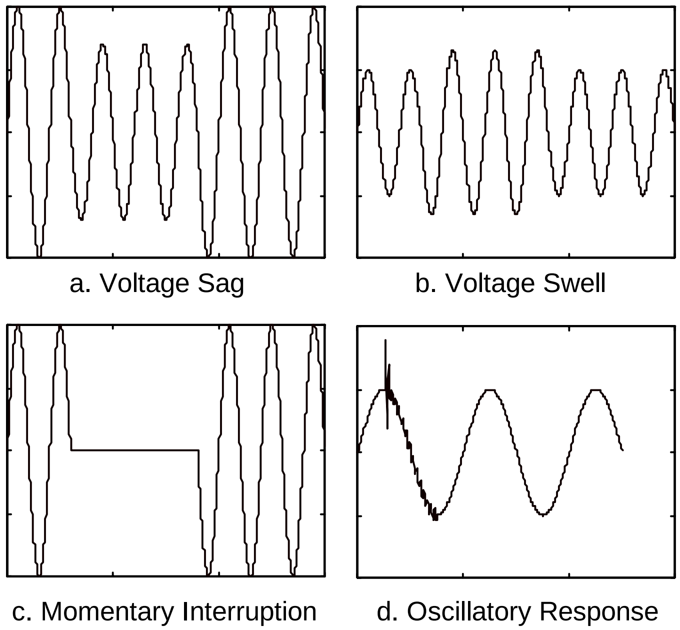

Figure 1. Transients that occur in supply voltage

Occurring individually[1], all these transients may be modeled as 4-parameter autoregressive (AR) processes[2] [2]. As RAM is usually limited in an energy meter, batch modeling is not preferred. Therefore, the recursive least squares (RLS) procedure to detect, classify and log these transients (time of occurrence, type and parameters). An additional advantage of the RLS procedure is that it converges quickly and requires a very few samples for accurate estimation/ tracking of model parameters. The parameters used to describe these transients can also be used to reconstruct their time-domain waveforms (if required).

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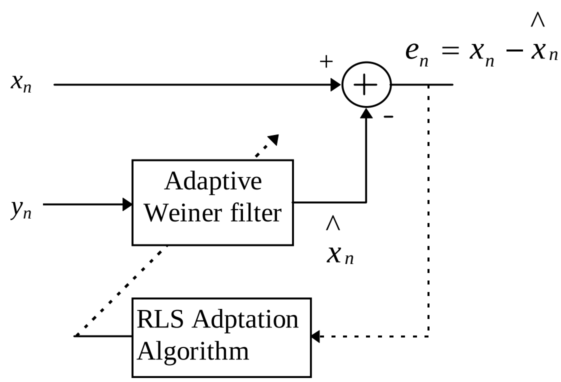
[1] We assume that the probability of simultaneous occurrence two or more events is negligibly small; thus, the event count (and power quality discount) is not significantly affected.

[2] For example, the oscillatory transient contains two sinusoids (at the line frequency and at the transient frequency) in very little noise and, if it has a very short rise and fall time as compared to the sample duration, may be modeled as a fourth order AR process).

2. Algorithm Description

The recursive least squares (RLS) algorithm [3], based on the minimization of a least squares criterion, is used to find the coefficients (model) of an unknown system with the help of a known system. The filter weights are optimal at each time instant *n*. The convergence factor (which determines the maximum rate of change of the input nonstationarity usefully tracked by the filter), along with reasonable computational complexity and numerical stability, makes the RLS procedure an ideal choice for transient detection in DSP-based electronic energy meters [4]. The adaptive implementation of a Weiner filter using the RLS is depicted in Fig. 2.



Fig, 2. Adaptive Weiner filter

We define the following terms [3]. The inverse covariance matrix is defined as

$$P = \frac{1}{\delta} \bullet I(M) \quad (1)$$

where *I(M) is M×M* identity matrix and δ is initialized to 0.01.

The *a priori* Kalman gain vector is

$$k_0 = \frac{P \bullet y}{\lambda} \quad (2)$$

where y is the input matrix and λ is the 'forgetting factor'. The likelihood variables are

$$\nu = y^T \bullet k_0$$

$$\mu = \frac{1}{(1+\nu)} \qquad (3)$$

The *a posteriori* Kalman gain vector is

$$k_1 = \mu \bullet k_0 \qquad (4)$$

With these definitions, the inverse covariance matrix is updated by

$$P \leftarrow \frac{P}{\lambda} - k_1 \bullet k_0{}^T \qquad (5)$$

The estimates of the input process, *x*, are

$$\hat{x} = h^T \bullet y \qquad (6)$$

where *h* are the optimal filter weights. The estimated error is

$$e = x - \hat{x} \qquad (7)$$

The optimal filter weights are updated by

$$h \leftarrow h + e \bullet k_1 \qquad (8)$$

The RLS adaptive procedure is described by (5) and (8).

3. The RLS procedure applied to transient detection and classification

Fig. 3 describes the transient detection, classification and logging procedure used in the electronic energy meter. First, a difference between the predicted *L*-cycle waveform and the current *L*-cycle block is computed. The difference is passed through an envelope detector and the envelope is compared with a threshold. The RLS procedure is then enabled during the transient duration to obtain estimates of a 4th-order autoregressive filter coefficients. This analysis suffices for oscillatory transients, voltage sag and swell and momentary interruptions when they occur individually (the 4th-order model does not suffice when these events occur in combination simultaneously).

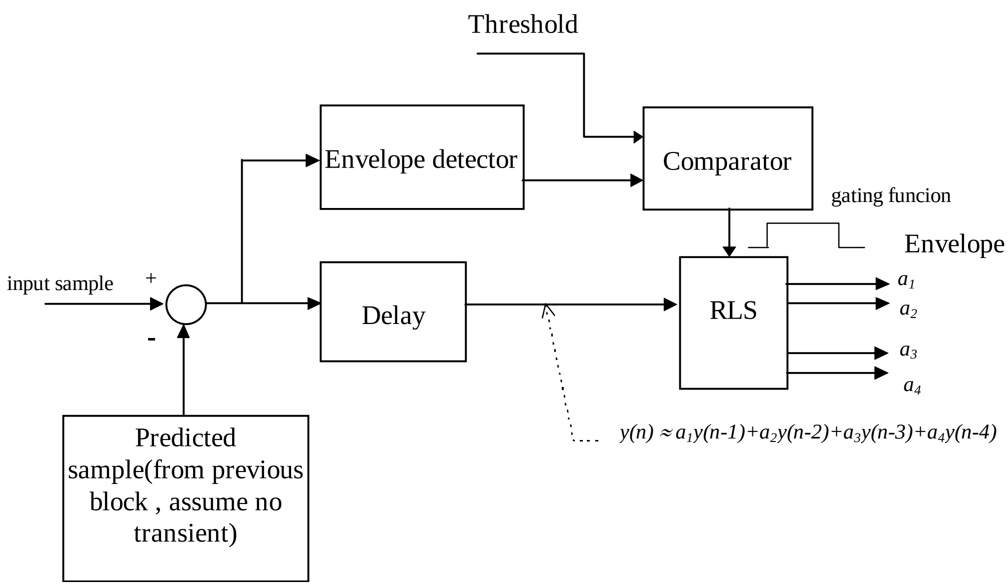


Fig. 3. Transient detection/ logging block diagram

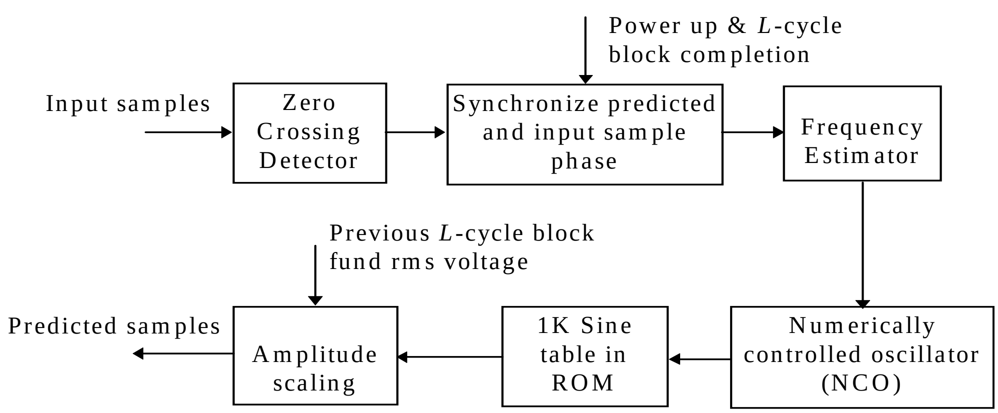


Fig. 4. Predicted Sample block diagram

The predicted waveform can be generated by two methods:

The first method generates these samples using an oscillator (lattice form 2^{nd} order resonant filter) from the estimated frequency and the fundamental magnitude (assume that harmonic magnitudes are less than 5% so that the peak-to-rms ratio, i.e., the crest factor, is not too high; then transients that change the fundamental [1] by more than 10% are detected). In this case, a reduced computation rate is obtained as the predicted waveform excludes harmonics (i.e., only the fundamental is the predictor). Despite this simplification, this method consumes excessive data memory and is computationally intensive.

An alternative method uses a suitable size ROM (1024 in the application), containing one cycle of a sine wave at nominal voltage magnitude. Fig. 4 describes the generation of the predicted sample. The zero-crossing detector (ZCD) helps estimate the frequency and synchronize the input and predicted waveform phases. Upon power up, positive zero crossing detection synchronizes the input waveform and sine table. The number of samples obtained from the ZCD over an *L*-cycle block is used to estimate frequency. A numerically controlled oscillator (NCO) generates an index into the sine table based on the number of samples over an *L*-cycle block. Index manipulation is as follows:

$$\text{ROMpointer+} = \text{ integer part}\left[\frac{\text{ROMlength} \bullet \text{L}}{\text{N}_\text{s}} + \text{fraction}\right]$$

$$\textit{if (ROMpointer >ROMlength) ROMpointer- = ROMlength} \qquad (9)$$

$$\text{fraction+} = \text{fractional part}\left[\frac{\text{ROMlength} \bullet \text{L}}{\text{N}_\text{s}}\right]$$

with initial values of *ROMpointer* and *fraction* zero. As the sampling frequency does not depend on the input line frequency, the positive zero crossing may occur upon negative to positive transition. If the *ROMpointer* is initialized to zero upon positive zero crossing, the input and predicted waveform may not be exactly synchronized in phase. As the sine wave is approximately linear near zero crossings, a properly scaled input sample can be used to fine tune indexing at the positive zero crossing instead of setting the *ROMpointer* to zero. This scaling factor is:

$$\text{Scalingfactor} = \frac{2^n \bullet 2}{\text{Romlength}}$$ where n is the ADC resolution in bits

$$\text{ROMpointer} = \frac{\text{inputsample}}{\text{Scalingfactor}} \tag{10}$$

A scaler multiplies the output of NCO so that the samples proportional to the fundamental RMS voltage of the previous L-cycle block. The amplitude scaling is:

$$\text{predictedsample} = \frac{\text{rmsvoltage}}{\text{nominalvoltage}} \bullet \text{ROMsample} \tag{11}$$

As the NCO output frequency is only an approximation to the input frequency, the difference between input and predicted waveform will increase with time (due to the residual frequency difference), and if uncompensated, will lead to the transient gate in Fig. 3 to switch ON, causing the detection of spurious transients. This may be obviated by synchronizing the predicted waveform with the input waveform every L-cycle block for a suitably chosen L. From model parameters, the waveform may be reconstructed by:

$$y(n) = a_1 y_{n-1} + a_2 y_{n-2} + a_3 y_{n-3} + a_4 y_{n-4} \tag{12}$$ [3]

4. Fixed Point Implementation

Care has to be taken in the selection of initial value of P in (1) and λ in (2), as if the dynamic range of any component of P exceeds 32 bits (double precision), computational complexity will be prohibitive (for triple or quadruple precision). Since any transient with duration greater than two line frequency cycles must be detected and classified [1], we limit the number of input samples used to estimate the model parameters to 100 (or 2 cycles at 2500 Hz sampling rate) even if the transient duration is longer in order to limit the dynamic range of P to 32 bits. Various transients were simulated in MATLAB™ to estimate the dynamic range of each variable

[3] Here y_{-1}, y_{-2}, y_{-3} and y_{-4} are stored/ transmitted along with the a's to describe the transient.

used in the RLS procedure. Table 1 shows each variable's dynamic range and resolution (for fixed-point implementation).

Variable	Integer (16-bit words)	fraction (16-bit words)
P	2	1
y	0	1
k_0	1	1
k_1	1	1
ν	1	1
μ	0	1
e	0	2
h	1	1

Table 1. RLS variables and their respective precisions

5. Results and Test Apparatus

Various transients are modeled using MATLAB™ (using 64-bit floating point arithmetic) and the DSP implementation (on an ADSP 2101, a 16-bit data bus, fixed-point DSP) and the parameter models are compared in Table 2. Plots of reconstructed waveform using Signion's ADSP-2101 based solid state electronic energy meter (SALEM) with its associated PC-based monitoring software are shown in Fig. 5[4].

[4] Momentary interruption does not form part of Table 2 or Figure 5 as in this case all coefficients are zero and the reconstructed samples will also be zero, making for uninteresting table entries and graph.

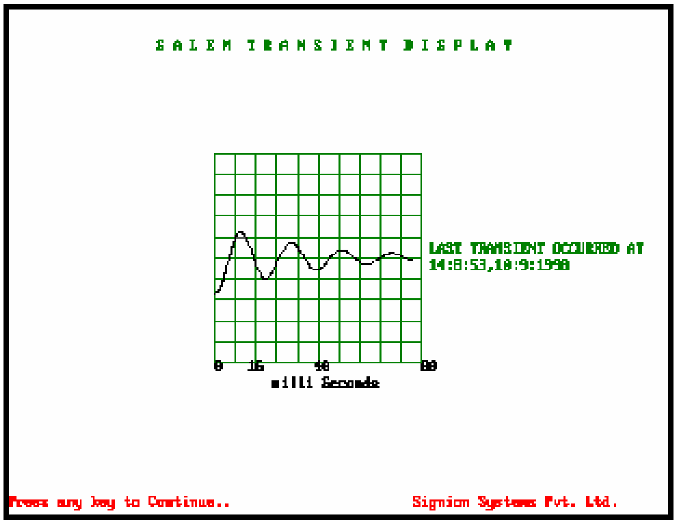


Fig. 5(a). Voltage sag

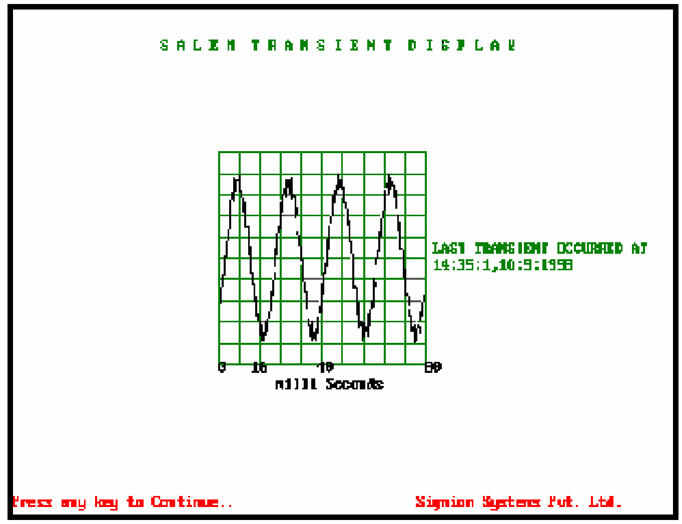


Fig. 5(c). Oscillatory transient

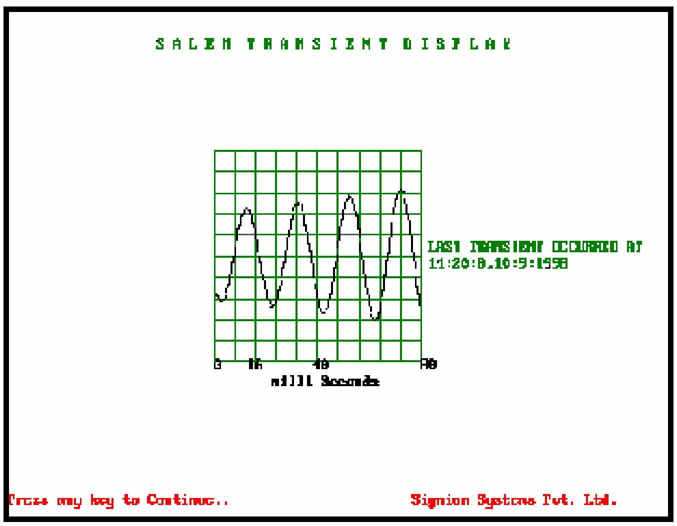


Fig. 5(b). Voltage swell

Transient type	MATLAB	DSP
Voltage sag	0.9695883 0.4898415 -0.0016758 -0.4973140	0.957230 0.480637 0.015366 -0.493637
Voltage swell	0.9838341 0.4903169 -0.0086441 -0.5051648	0.997223 0.464844 -0.000519 -0.501358
Oscillatory transient	0.3662027 1.2100140 0.3661462 -0.9994308	0.367706 1.207870 0.366592 -0.999771

Table 2. Coefficient values for various transients

Program memory RAM (24-bit wide) used by the transient detection module is 429 words, sine table ROM used is 1024 (16-bit) words and the total RAM used for the RLS variables, the filter and the gating function is 199 16-bit words. MIPs required when the gating function is operating alone (i.e., no transient is present) is 3.81 MIPs. When a transient is being processed, the peak MIPs required is 5.45 MIPs. The MIPs figures are for a 2500 Hz sampling rate and would increase almost proportionately for higher sampling rate.

For immunity[5], [1] defines swells or sags for periods greater than ½ line frequency cycle. Whether this definition should be applied to tariff meters (to determine power quality discounts) as well is yet to be decided. In the event that only longer transient (> 2 line frequency cycles) events are to be detected and classified, the approach described here is fully compliant. However, should transient definitions in [1] be directly applied to tariff meters, a minor modification to our procedure is as follows:

1. The envelope detector's time constant is reduced so that ½ cycle transients are detected.
2. Determination of RLS parameters is only done for those transients greater than 2 nominal line frequency cycles.
3. For transients less than 2 cycles, waveform comparison is used to classify the transient as sag, swell, momentary interruption or oscillatory transient. Since no RLS parameters are computed, the attributes of the transients (decay rate, frequency, etc.) are not computed.

[5] Although the standard specifies test levels and durations, *particular test levels and durations are not specified*; these are defined by *product committees*. These committees are comprised of a group of manufacturers with similar products. Our approach here is to apply IEC-1000-4-11, but to choose durations and test levels so that the "disturbances" count may be a useful measure used to compute tariff discounts.

Since the formulation of standards for power transient immunity, many transient generators have become available allowing the effectiveness of our algorithms implemented on a tariff meter to be tested. Alternatively, sag and swell circuits can easily be fabricated using low-cost components. An example sag/ swell generator, using thermistors, is shown in Figure 6, while an example oscillatory transient generator is shown in Figure 7.

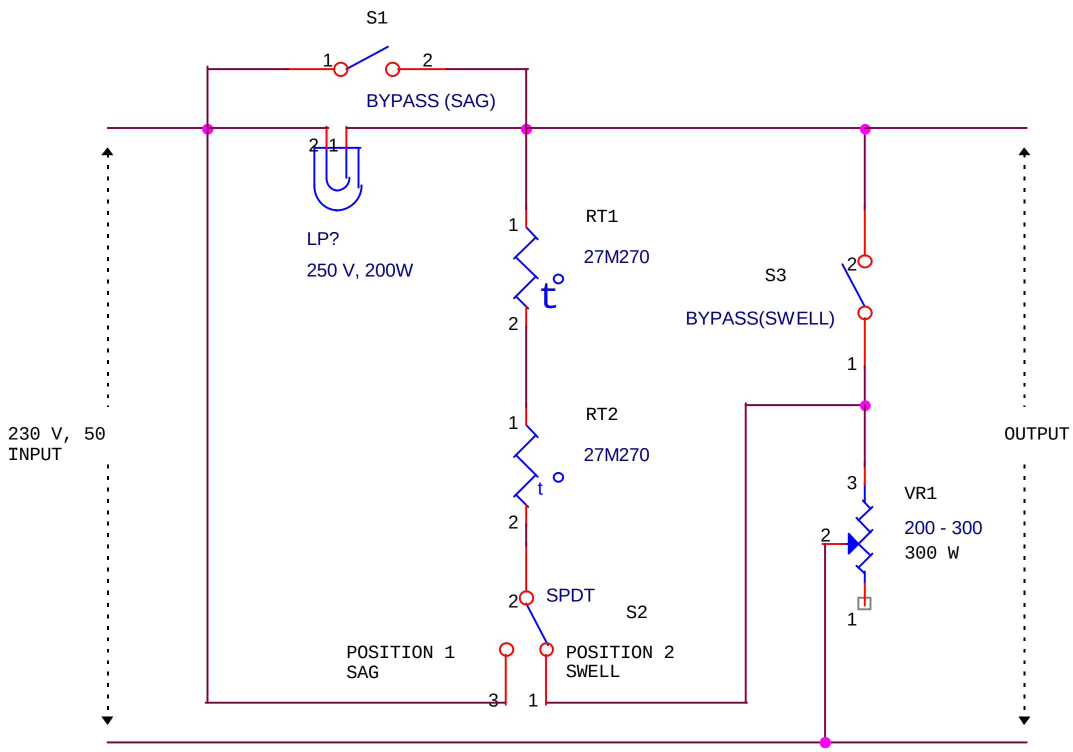


Figure 6. Sag/ Swell Generator

In Figure 6, initially S1 must be ON, S2 in position 1, S3 must be ON. To generate a sag S1 should be switched OFF. The time constant of the sag may be varied through potentiometer R1. From this condition, switch S2 to position 2, allow some time so that thermistor RT1 and RT2 reach ambient. Now, a swell may be generated by switching S3 off. The time constant of the swell may be varied through potentiometer R1. To cool the thermistors again, S2 should be switched to position 1 and S1 should be ON. The process may be repeated for sags and swells with varying time constants.

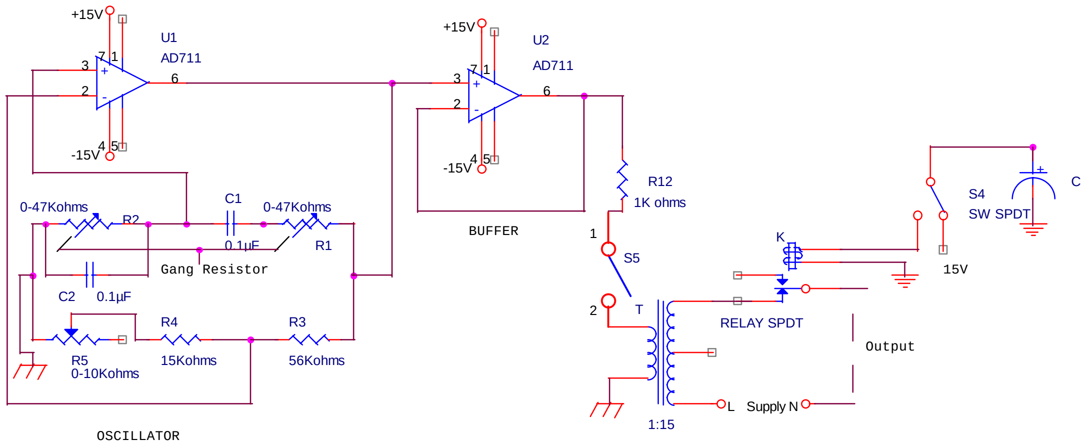


Figure 7. Oscillatory transient generator

In Figure 7, if switch S4 in position 1 and S5 is ON, the circuit generates an oscillatory transient. A Wein bridge oscillator generates the oscillations at the desired frequency, and these oscillations are coupled to the primary of a step-up transformer (turns ratio of 1:15) through a buffer. The line frequency voltage is then added in series with the secondary of the transformer resulting in a oscillatory transient at the output. The frequency of the oscillations can be varied by varying ganged resistor, while resistor R5 is varied to maintain unity loop gain of the oscillator. When switch S5 is OFF and S4 is thrown to position 2, the capacitor C discharges through the relay thereby shutting OFF the normally ON relay producing a momentary interruption of the supply voltage at the output.

6. Conclusion

The effectiveness of the RLS algorithm in terms of meeting the transient detection and classification requirements of [1] is described. The proposed method meets these requirements with substantial data reduction over conventional waveform capture schemes. Implementation and complexity related issues on a fixed-point DSP are also presented.

Acknowledgment: We thank C. G. Hiremath and V. Hari Kishan for their comments and suggestions.

References:

[1] IEC-1000-4-11, *Testing and Measurement Techniques to verify immunity of electrical products from voltage dips, short interruptions and voltage variations.*

[2] John G. Proakis, Dimitris G. Manolakis, *Digital Signal Processing, Principles, Algorithms and Applications*, pp. 823-834, Macmillan Publishing Co., USA, 1992.

[3] Sophocles J. Orfanidis, *Optimum Signal Processing, An Introduction*, pp. 404-477, McGraw Hill International Edition Book Co., Singapore, 1990.

[4] M. Nagaraju, T. Praveen Kumar, "Networked electronic energy meters with power quality analysis", pp. 45-57, *Power Quality '98*, Hyderabad, June 1998.`