Low-cost Rectifier for Measuring of AC Voltage or Current Frequency Compensation Proposal

Martin Pospisilik, Pavel Varacha, Milan Adamek

Abstract**—**Usually the rectifiers are the most problematic devices of the low-cost measurement instruments. The features of a simple full wave rectifier construction with an operational amplifier are usually determined by the rectifying diodes and the slew rate of the operational amplifier and unfortunately, they suffer from the dependence on the amplitude of the measured signal. Of course, special topologies as well as current-mode operating devices can be used, but this paper considers the possibility of how the frequency range of a cheap conventional rectifier can be broadened. It is supposed that the rectifier operates on a single signal level at which it can be well frequency compensated. The measurement is processed indirectly by a microcontroller that changes the amplification factor of a preamplifier in order the target level was achieved. Subsequently the measured value is computed from the amplification factor required to achieve the target level. However, this approach, although it looks simple, can result in very time consuming processing if the frequency of the measured signal is too low. Therefore several approaches and proposals are discussed. The authors believe that the proposed solution, although quite complex, can bring satisfactory results when used in multimeters equipped with a microcontroller that employ a three digit display and are capable of operation up to 100 kHz or 1 MHz in dependence on the construction of its internal circuits.

Keywords**—** Mean Value Measurement, Frequency Dependence, Rectifier, Successive Approximation, Voltmeters

I. INTRODUCTION

THERE are many methods how to improve the parameters of rectifiers employed in AC voltmeters or amperemeters. Several designs are based on usage of fast conventional devices. Also, rectifying in current mode became popular, employing operational transconductance amplifiers (OTA) [1]. Maintaining their parameters, the approach described in this paper allows employing a wide variety of rectifiers. Moreover it helps to gain the best possible results that can be achieved with the particular rectifier because this rectifier is always operated at single level which makes the frequency compensation easier to apply. The main idea is not to measure the level of the voltage, but to amplify the measured signal to the required level and, subsequently, to calculate its level from the applied amplification factor. Although this approach can be time consuming at low frequency signals, it allows exploiting the employed rectifier as much as possible.

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II. PROBLEM FORMULATION

For the purposes of this paper let us consider the simple construction of the rectifier using a low cost operational amplifier and diodes as shown below.

The circuit depicted in Fig. 1 is a popular absolute value amplifier that can operate as a full-wave rectifier, if the following condition is fulfilled [2]:

$$\frac{2 \cdot R4}{R6} = \frac{R2}{R1} \quad \cap \quad R2 = R3 \qquad (1)$$

The waveforms at the input and the output of the circuit, obtained by simulation, are shown in Fig. 2 and Fig. 3. As can be seen in the figures the circuit depicted in Fig. 1 works satisfactorily at low frequencies.

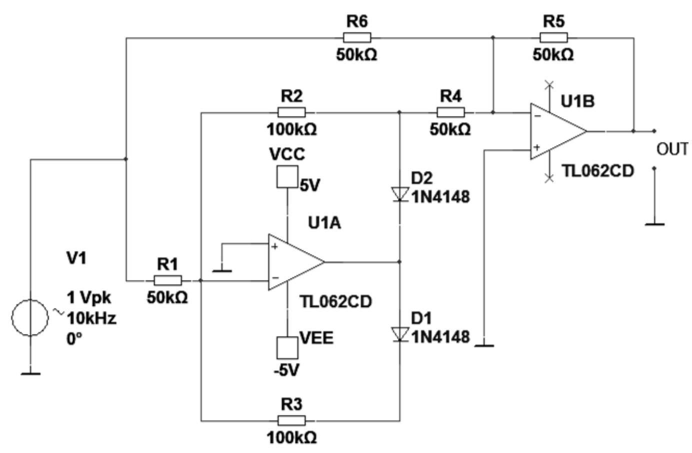

Fig. 1 – Simple full-wave rectifier simulation schematics

As can be seen in Fig. 2 and Fig. 3 the circuit depicted in Fig. 1 works satisfactorily at low frequencies. However, several problems occur when the frequency of the processed signal increases. If no compensation is applied, the output of the rectifier becomes out of phase, and, moreover, the mean voltage level at the output changes significantly as the waveform is distorted. This happens due to phase shift of half-wave discriminator based on U1A operational amplifier, which is caused not only by the operational amplifier itself, but also by the non-linear capacities that occur in junctions of D1 and D2 diodes. This phenomenon can be partly compensated by adding capacitors to the circuitry, but the non-linearity of the diodes does not allow employing the rectifier at wide range of amplitudes. In Fig. 3 there is also a sample of waveform that is obtained at the output of the rectifier modified according to Fig. 4. Additional capacitors C1 and C2 were employed to cancel the effects mentioned above and, as can be seen, although the waveform is distorted, the mean value is closer to the real one and the signal at the output is in phase with the input.

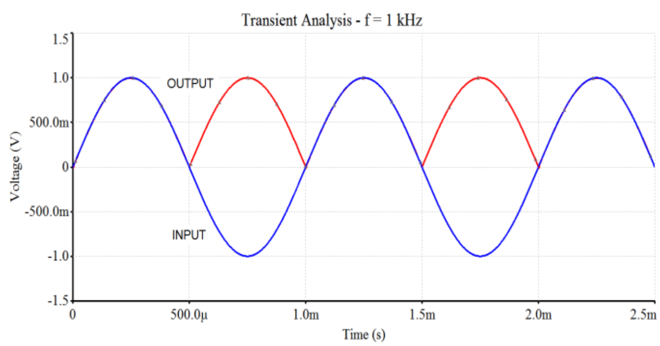

Fig. 2 - Full wave rectifier from Fig. 1 input and output at f = 1 kHz (simulation)

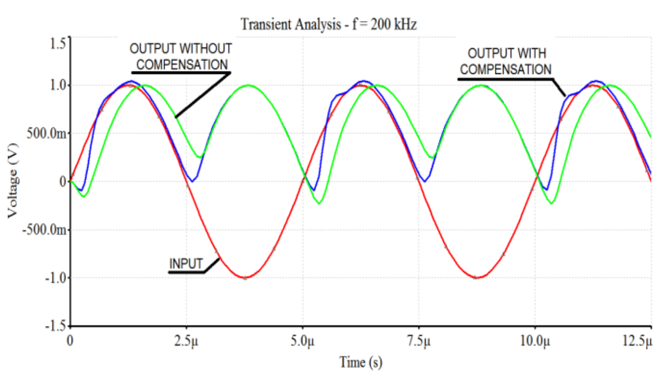

Fig. 3 - Full wave rectifier from Fig. 1 input and output at f = 1 kHz (simulation)

How the output mean value depends on the frequency and level of the input signal has been proven by a set of simulations. The circuit depicted in Fig. 4 was fed with harmonic signals of different voltages within the range of 10 mVp to 1 Vp and different frequencies within the range of 1 kHz to 2 MHz. The attenuation of the output mean level, expressed in dB relative to the results obtained at the frequency of 1 kHz is shown in Fig. 5. It is obvious that at high frequencies the frequency compensation works properly only for one level.

Using an additional circuit modelling the reciprocal transfer function at the input of this rectifier, at the level of approx. 1 Vp it would be capable of operation up to 1 approximately 1 MHz. This evokes the idea to make the voltmeter or amperemeter based on this rectifier work in that way the level of the rectified signal was always the same.

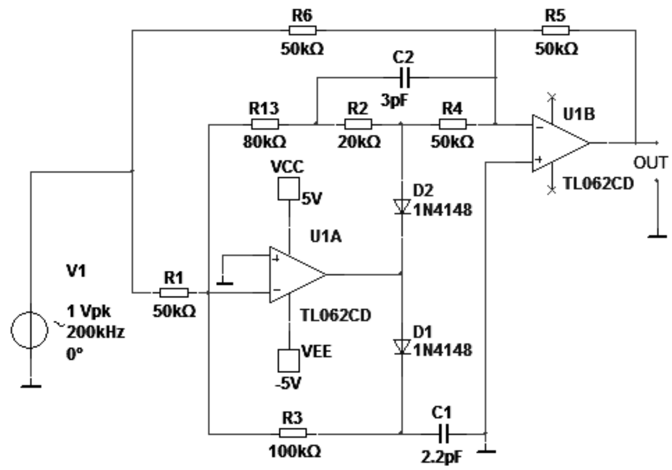

Fig. 4 - Modified full wave rectifier with frequency compensation

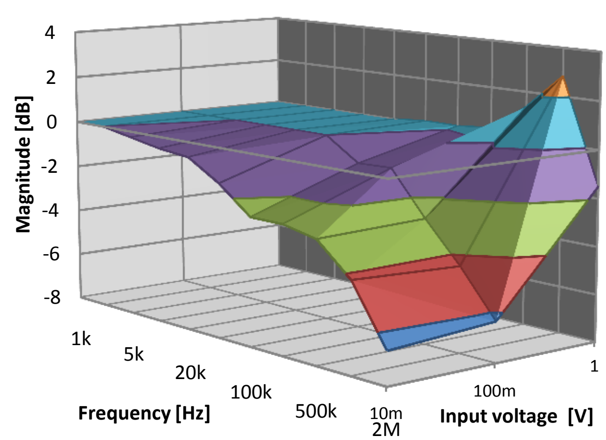

Fig. 5. - Attenuation of the frequency compensated rectifier at different voltage levels and different frequencies

III. Problem Solution

To obtain the best possible frequency range there is a need for analysing the transfer function of the rectifier for one precisely defined level. Let us consider the level of 1 VP. From the simulations the result of which is depicted in Fig. 5 we know the following compensation points: at 200 kHz there starts the rise of the magnitude with the gain of + 0.25 dB, at the frequency of 1 MHz there is a peak of gain, reaching up to + 2.7 dB. If the accuracy is not critical, the compensation can be made by a simple RC integral member or a simple preamplifier as shown in Fig. 6. In simulations of the preamplifier also the parameters of the operational amplifier were considered. Using the full wave rectifier from Fig. 4 together with the simple preamplifier with additional frequency compensation from Fig. 6, the frequency response depicted in Fig. 7 can be achieved.

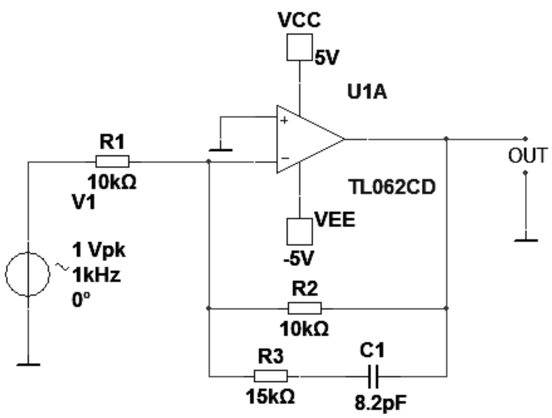

Fig. 6 - Simple preamplifier for additional frequency compensation

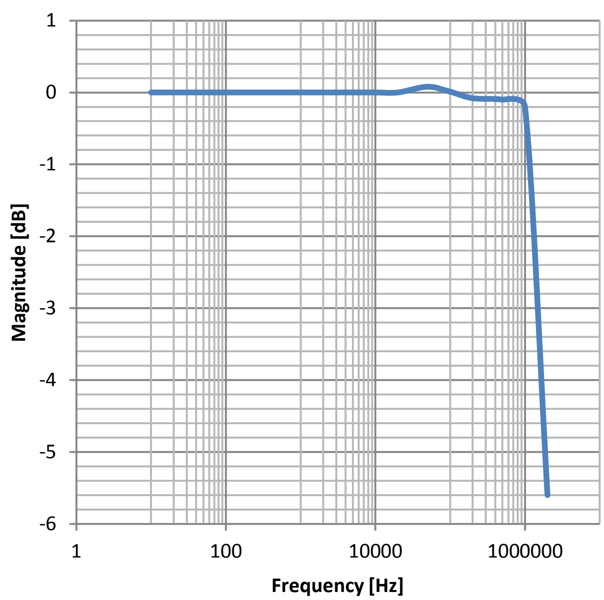

Fig. 7 - Frequency response of the well-compensated full wave rectifier from Fig. 4.

As can be seen in Fig. 7, the frequency response is within the range of – 0.2 to + 0.1 dB for the frequencies up to 1 MHz. This corresponds to the uncertainty of approx. 2.5 % in the worst case. This error may be lowered by using more sophisticated methods of frequency compensation. However, this is an example of an ultra-low cost full wave rectifier. Provided better topologies and devices are used, the results will improve adequately.

A. *Basic approach*

After stating that there are two degrees of separation obvious from the rectifier analysis, the frequency dependence and the amplitude dependence, and after deciding to cancel one of those – the amplitude dependence, there occurs a problem how to make the rectifier working always at the same level for which it is calibrated. This problem can be solved by employing a microcontroller and an amplifier with externally controlled gain. The block diagram of the suggested voltmeter disposition can be seen in Fig. 8.

The block diagram of the suggested voltmeter consists of several blocks. The input buffer with a prescaler serves to set the range of measurement and the proper input parameters, for example the input impedance.

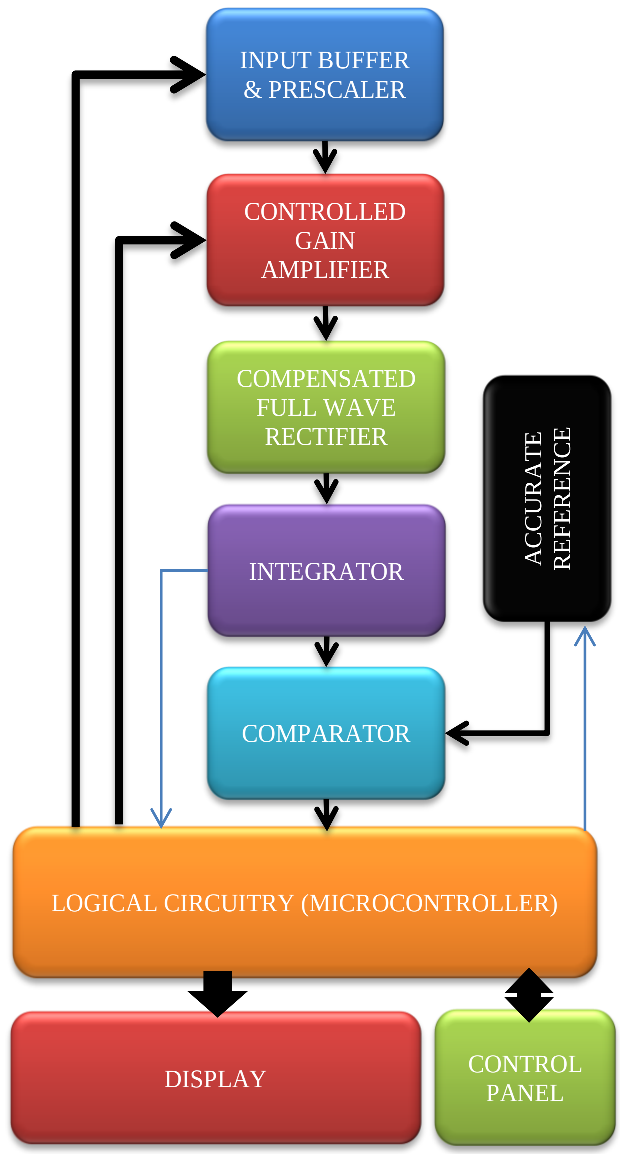

Fig. 8 - Block diagram of the suggested voltmeter disposition

Then there is the controlled gain amplifier the gain of which can be precisely set by the logical circuitry, which can be realized by means of a microcontroller. The controlled gain amplifier can be habitually frequency-compensated without the influence of the signal level. At the output of the controlled gain amplifier there is the full wave rectifier to be operated at a single level. Its output drives the integrator to produce the mean level of the measured signal. Of course, other processing units can be employed, for example the peak detector. At the output of the integrator the comparator unit can be found. The comparator compares the level at the output of the integrator to the voltage reference that is tuned to the level at which the full wave rectifier should operate. It gives the logical circuitry information on whether and when the reference level was matched. The logical circuitry drives display, input buffer with prescaler and the controlled gain amplifier. It is controlled through the user control panel. The user can control several functions like setting of the prescaler, freezing the displayed value etc.

The basic algorithm of operation is as follows. When turned on, the logical circuitry sets the lowest gain and waits for the response from the comparator. If, after the appropriate amount of time, the desired value is not reached at the output of the integrator, the gain of the amplifier is increased by 1 step and the waiting loop is processed again. This process is repeated in a cycle until the desired value is found. When the value is found, the logical circuitry takes into account the gain of the controlled amplifier that is currently set and the setting of the prescaler and calculates the estimated value to be measured. This value is then displayed on the display.

The number of the gain steps depends on the required measurement accuracy. It can be determined by the number of digits at the display. For low-cost voltmeters (amperemeters), the accuracy of 3 digits can be considered as satisfactory (000 to 999). If 3 digits are enough, 10 bit resolution of the gain will probably be satisfactory, providing 1,024 levels of gain setting.

The main disadvantage of this solution consists in its slowness. In order the integrator worked properly, its time constant shall be much higher than the period of the slowest signal to be measured. If the frequency of 1 kHz is considered, the period of the pulses at the output of the full wave rectifier is 500 μs (two pulses are gained from one period). If the 1 kHz is the lowest measurable frequency, the integrator with time constant of at least τ = 20 ms shall be used. Such integrator gives the stable value after approximately 5τ, which is 100 ms. The ripple at the cutoff frequency is then approximately 0.5 %. In the worst case in which 1000 combinations must be cycled through, one measurement requires the following amount of time:

$$t_{meas} = 1000 \cdot 5 \cdot \tau = 100\ [s] \qquad (2)$$

Obviously, such value cannot be implemented. However, the basic concept introduced in Fig. 8 can be slightly improved in order it operated faster. First of all, successive approximation algorithm shall be employed. This will reduce the number of approximation steps to the number of gain control resolution in bits plus one [3]. Moreover, the fact that the full wave rectifier works independently on the input level up to the frequency of approximately 4 kHz shall be taken into account. In Fig. 8 there are two thin arrows symbolizing the connection between the integrator output and the input of the A/D convertor in the microcontroller and the connection between the microcontroller and the accurate voltage reference source. The microcontroller then estimates the frequency of the measured signal. If the frequency is lower than 4 kHz, it does not change the gain of the controlled amplifier. Instead of this it periodically changes the level of the voltage reference, for example by driving it by a saw signal generated by means of a PWM modulation. The period of this signal can be for example 10 ms so up to 10 measurements per second may be realized. The value displayed at the display complains to the level of the PWM modulation at which the match at the comparator has been achieved. On the other hand, if the frequency is higher than 4 kHz, the voltmeter operates as suggested above, employing the successive approximation. In the first step the gain of the controlled amplifier is set to the intermediate value and the logical circuitry (microcontroller) decides if the gain shall be increased or decreased according to the output state of the comparator. In each step the interval is halved until the desired value is found. It should be found in no more than 11 steps. Considering the cutoff frequency of 4 kHz the estimated time constant of the integrator is τ = 5 ms. The time required to process the measurement is then

$$t_{meas} = 11 \cdot 5 \cdot \tau = 0{,}275\ [s] \qquad (3)$$

Therefore up to 3.6 measurements per second can be realized.

When peak detector is used instead of the integrator, the times needed to process the measurement are much shorter; only several periods of signal are usually needed to obtain the maximum value.

B. Optimized approach

On the basis of the discussion mentioned above there is a crucial need for optimization of the proper amplification factor selection in order the number of measurements was satisfying. In order to optimize the measurement, several changes should be introduced in the basic idea depicted in Fig. 8. These changes are as follows:

1) Improved input buffer and prescaler block

The input buffer and prescaler block should be autonomous in selecting the proper range. Two resettable peak detectors and comparators should detect the overvoltage and undervoltage, resulting in selecting the proper scale ratio. Subsequently the microcontroller should get a confirmation bit allowing it to start of the measurement. The flowchart of the input buffer and prescaler is depicted in Fig. 9. This operation can either be processed by the microcontroller in parallel to its main operation loop or can be processed autonomously using a few logical gates and a clock source.

The operation principle is simple. In a regular period, for example 1 second, the outputs of the overvoltage and undervoltage comparators are checked and if the overvoltage or undervoltage is detected, the scale ratio at the input of the measuring device is changed accordingly. Meanwhile the measurement is disabled in order the subsequent blocks in the chain were not driven into saturation. After each scale change the appropriate peak detector is reset and prepared for the further operation. Selecting of the proper scale ratio (measurement range) can be indicated on the display of the meter or by additional LEDs, showing also the range that is actually selected.

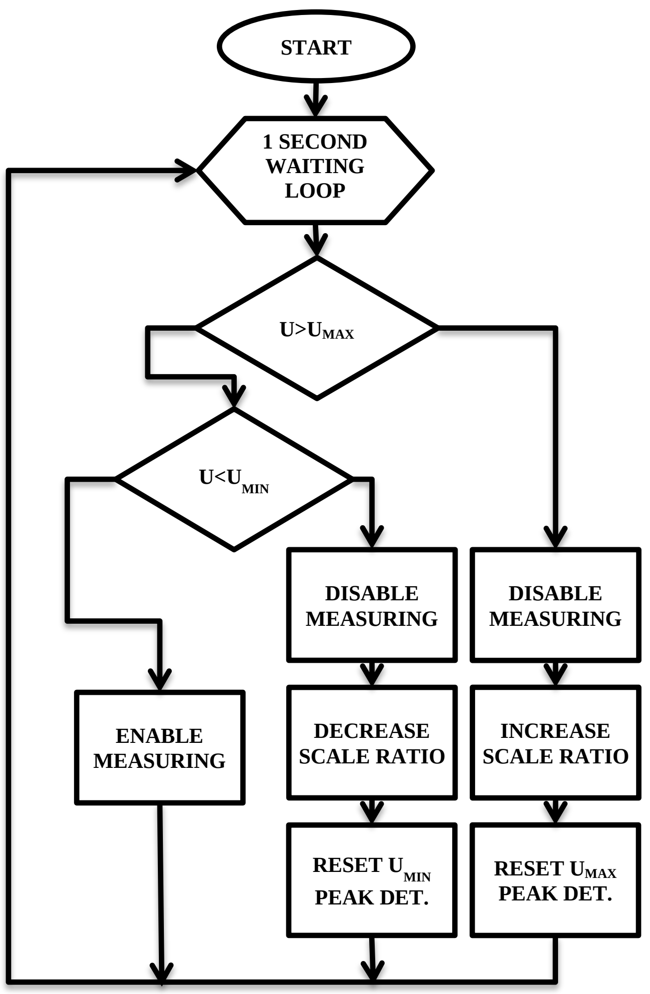

Fig. 9 – Autonomous input buffer and prescaler operation flowchart

In the Fig. 10 a block diagram of autonomous input buffer and prescaler constructed with the aid of logical gates is depicted. The prescaler is able to change the scale ratio in multiples of ten. The most probable ranges will be 100 mV, 1 V, 10 V, 100 V and 1 kV, resulting in the scale ratio of 1:1, 10:1, 100:1, 1,000:1 and 10,000:1. The overvoltage protection and the suitable input impedance are assured by the input buffer circuit. The prescaler includes the switch enabling to select the appropriate scale ratio. The proper scale ratio is selected by the binary number at the output of the counter. The state of the counter can be increased or decreased by the logical signals obtained from the synchronous reset/set circuits. The same signals initiate resetting of the peak detectors. If any of the reset/set circuits' outputs is in H state, the measuring must be disabled. Therefore there is a "disable measuring" bit the microcontroller is fed with.

Provided the prescaler can remain in one of five states and therefore no more than 4 state changes are needed to find the appropriate state, when the clock frequency is 1 Hz, the proper initialization of the prescaler will take no more than 5 seconds which is acceptable.

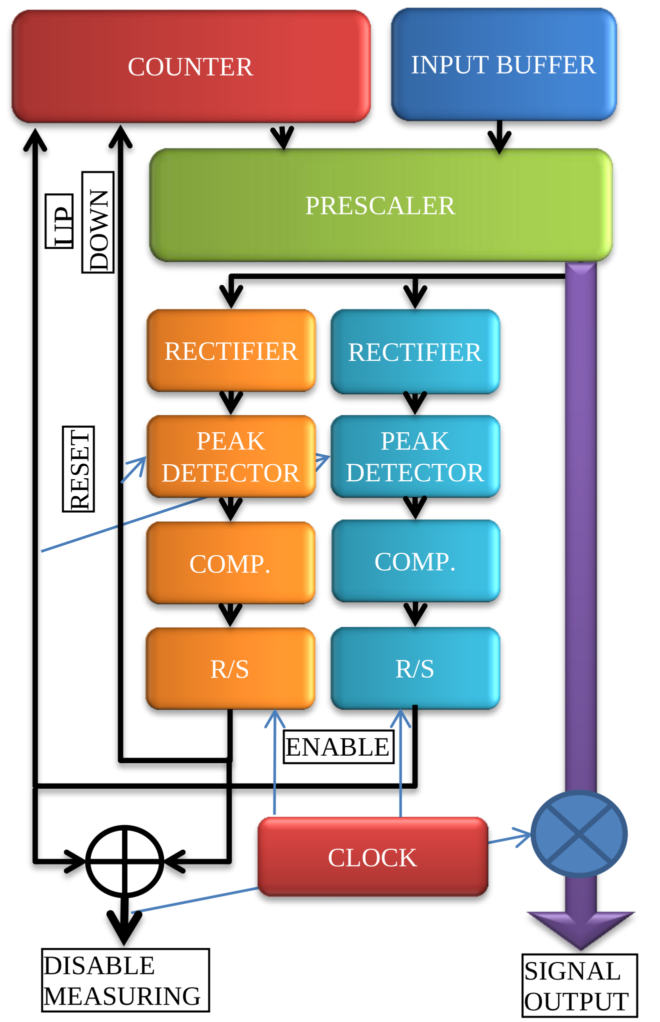

Fig. 10 – Block diagram of autonomous input buffer and prescaler constructed with the aid of logical gates

2) Interval division

In the text above the problem of long time period needed for measuring of low- frequency signals is mentioned (see (2)). As stated above the solution may lie in the configuration that enables to determine the measured signal frequency. According to this frequency on of the following methods would be used:

- direct measurement for low frequencies (< 4 kHz),
- indirect measurement for high frequencies (≥ 4 kHz).

The direct measurement consists in setting the controlled amplifier gain to a single level and conventional measuring of the signal amplitude. The indirect measuring then consists in selecting the proper amplification factor so the signal amplitude was as required, assuring the rectifier operates at one level for which it is frequency compensated.

However, such solution would, for the construction according the diagram in Fig. 8, require a precise controlled threshold reference level generator to feed the comparator. This would probably make the whole construction too complex and expensive, so it would be nonsense to call it "low-cost".

Instead a compromise solution may be applied. It consists in rough pre-division of the measurement range into 16 intervals by cheap fast-response comparators. Provided the measurement range is 10 bits wide (1,024 steps), dividing it into 16 intervals would shorten the search space by 4 bits to 64 steps. When a method of successive approximation is applied now, no more than 7 steps are needed to find the proper value. This is because of the successive approximation feature consisting in the fact that the longest time to achieve the proper result corresponds to the number of resolution bits plus one [3].

Anyway, at low frequencies the measurement will not be fast enough, resulting in the need for frequency detection. When the frequency detection is applied, the time constants of the integrator and therefore the measurement speed can be different according to the frequency of the measured signal.

3) Frequency detector

From the above mentioned considerations it is obvious that there is a need for a frequency detector that will, with a reasonable hysteresis, determine the frequency of the measured signal. According to the frequency the time constants of the integrator can be changed as well as the measurement periods. Considering the block diagram depicted in Fig. 8, the frequency detector should be implemented between the Input buffer and prescaler block and the Controlled amplifier block. It should be of autonomous operation as well as the Input buffer and prescaler, having the ability to block the measurement until the frequency of the signal is determined.

Provided the frequency detector is able to distinguish among at least 3 frequency ranges, the interval division as stated in the previous subchapter will be probably not needed any more, resulting in even lower price of the device. In case the Interval division is implemented, it should be operated only on frequencies of the frequency range I and II according to Tab. 1. Operating the Interval division comparator network at high frequencies would be quite expensive due to the need of fast comparators. By combining the Interval division with the Frequency detector the following number of measurements can be achieved:

- 1 measurement per minute for the signals the frequency of whose is below 20 to 30 Hz,
- 1 measurement per second for the signals the frequency of whose is between 20 to 30 Hz and 200 to 300 Hz (considering the hysteresis of the Frequency detector),
- 7 measurements per second for the signals the frequency of whose exceeds the threshold of 200 to 300 Hz (the Interval division is off).

The suggested output of the frequency detector and the appropriate time constants are enlisted in the following table.

Table 1 – Suggested frequency ranges

Frequency range	Parameters	
I	Lowest frequency	0,5 Hz$^{1)}$
	Highest frequency	30 Hz
	Integrator time constant	1 s
	Duration of measurement$^{5)}$	40 s$^{2)}$ 55 s$^{3)}$
	Measurement period	1.4 / min$^{2)}$ 1 / min$^{3)}$
II	Lowest frequency	20 Hz
	Highest frequency	300 Hz
	Integrator time constant	125 ms
	Duration of measurement$^{5)}$	1 s$^{2)}$ 1.4 s$^{3)}$
	Measurement period	1 / s$^{2)}$ 0.7 / s$^{3)}$
III	Lowest frequency	200 Hz
	Highest frequency	1 MHz$^{4)}$
	Integrator time constant	12.5 ms
	Duration of measurement$^{5)}$	0.1 s$^{2)}$ 0.14 s$^{3)}$
	Measurement period	10 / s$^{2)}$ 7 / s$^{3)}$

There are the following notes to the table 1:

$^{1)}$ The lowest frequency is determined by the time period of the integrator and the maximum allowed ripple of the integrator voltage that is considered to be lower than 0.5 %. If not so low frequencies are expected, the time constant of the integrator may be shortened, resulting in shorter measurement duration.

$^{2)}$ Provided the interval division is applied.

$^{3)}$ Provided the interval division is not applied.

$^{4)}$ The upper limit is determined by the features of all the considered circuits. According to Fig. 7 it is theoretically possible to reach satisfactory performance of the rectifier constructed of cheap conventional devices at the frequencies up to 1 MHz.

$^{5)}$ As stated above, in order the voltage ripple at the output of the integrator was lower than 0.5 %, the time constant is chosen correspondingly to the doubled period of the measured signal of the lowest possible frequency and one step of the measurement is at least five times longer than the time constant of the integrator.

4) Optimized approach configuration and operation

The final configuration resulting from the considerations enlisted above is depicted in Fig. 11. The measuring device should operate as follows:

1. Input buffer and prescaler block sets the appropriate scale ratio. This can take up to 5 seconds. During the scale selection the microcontroller is fed with an information bit that means the signal at the output of the prescaler is attenuated to zero. When the proper

ratio is selected, the amplitude of the signal is between 8 to 80 % of maximum provided the input voltage is between 8 mV to 800 V (provided the 5 ranges as described above are employed). If the voltage range is exceeded, the disabling bit is still active and the device does not work.

2. Once the signal output from the Input buffer and prescaler is enabled, it feeds the input of the Frequency detector block. The Frequency detector determines the frequency of the signal. Until done, its output is also blocked and the proper information bit is sent to the microcontroller.

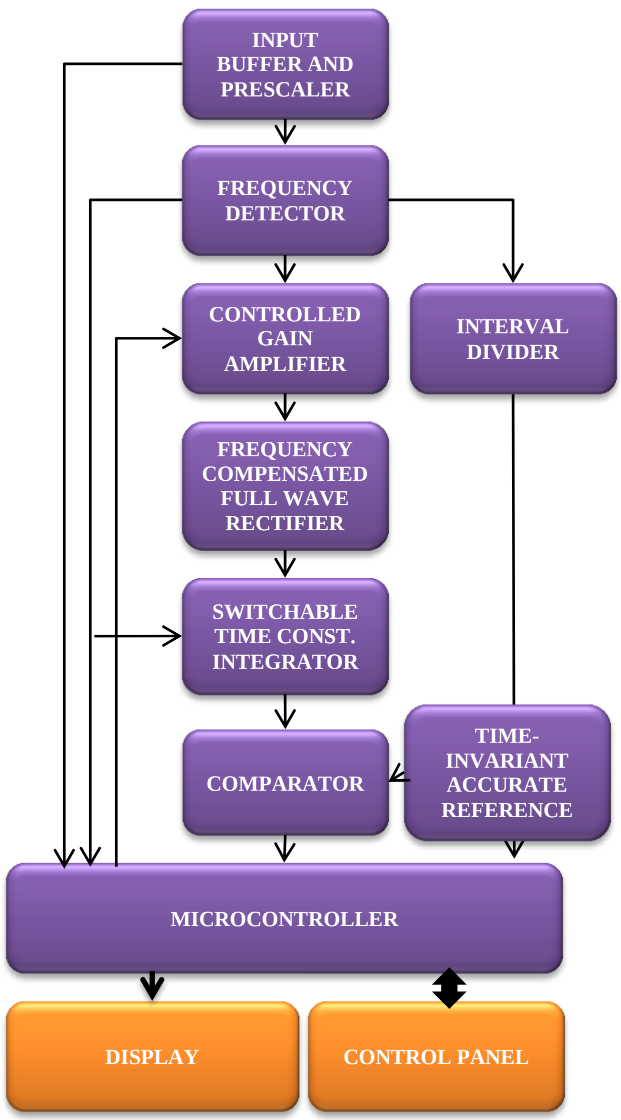

Fig. 11 – Optimized configuration of the suggested voltmeter disposition

3. According to the frequency of the measured signal the frequency detector sets the appropriate time constant of the integrator. The microcontroller changes the measurement period accordingly.
4. A short time after the frequency is determined and the scale ratio is set the output of the frequency detector block is enabled, feeding the Controlled gain amplifier and the Interval divider. The Interval divider is an optional block consisting of an autonomous, not frequency compensated, full wave rectifier, an integrator and 16 comparators. Its output is a 4 bit word giving the microcontroller information in which range the result search can be restricted. This information is valid only at frequency ranges I and II (see Tab. 1), improving the measurement speed up to 30 %.
5. The microcontroller sets the amplification factor of the controlled amplifier to the middle of the interval, either the interval is restricted by the Interval divider or the result search is processed in the full scale.
6. The output of the Controlled gain amplifier feeds the Frequency compensated full wave rectifier that drives the Switchable time constant integrator. After a period of time that is five times longer than the selected time constant of the integrator, the output of the comparator giving the information whether the target level defined by the Time-invariant accurate reference was achieved or not is considered to be valid and is evaluated by the microcontroller.
7. If the level was exceeded, the microcontroller decreases the amplification factor to one halve of the previous level and waits for the next time period for the result. If the level was not exceeded, the microcontroller increases the amplification factor to 150 % of the previous level and waits for the next time period for the result.
8. The step 7 is repeated until the result is achieved or for 8 or 11 steps (this number depends on the utilization of the Interval divider) in whose the result must be achieved with acceptable error.
9. When the measurement finished, so the result was found, the resulting voltage level is calculated from the settings of the prescaler and the amplification factor of the Controlled gain amplifier. The calculated number is the displayed on the display.
10. If the frequency or the level of the measured signal was not changed significantly (this would reset the system to the state described in step 1), the measurement is processed repeatedly according to step 7 with the time period corresponding to the frequency of the measured signal (seeTab. 1).

C. Controlled gain amplifier

For the proper function of the above mentioned voltmeter or amperemeter configuration the construction of the controlled gain amplifier is crucial. The basic requirements are as follows:

- flat or easy to be compensated frequency response,
- possibility of gain setting in the range of at least 1 to 1/1,000,
- setting by 10 bit word,
- low noise.

From the above mentioned considerations the following restrictions result:

- High precision digital potentiometer must be used,
- In order the high frequency range was ensured, the amplification factor cannot be high in any case.
- Combination of the requirement for the high frequency range and high gain range results in the construction that operates with amplification factor lower than 1.

In order to meet all the considerations, it seems that the most convenient way consists in constructing the attenuator that is connected at the front end of an amplifier with a fixed gain. Such amplifier can be simply frequency compensated. The attenuation factor must be capable of setting in 1,000 steps. The highest disadvantage of such solution is that the attenuation cannot be set in a linear way, but must be of a parabolic response, because not the amplification A but the attenuation 1/A is processed.

The construction of the controlled amplifier exceeds the range of this paper and will be published separately.

IV. Conclusion

In this paper one of the possible approaches to bandwidth of a low-cost full-wave rectifier utilizable in cheap voltmeters or amperemeters expansion is discussed. By employing the suggested algorithms and device disposition, the mean values of the signals with frequencies up to 1 MHz can be theoretically measured with the error lower than 2.5 %. At first glance this may not seem to be a success, unless we consider how cheap and easy to purchase devices were used in the simulations. The proposed disposition improves the parameters of any full-wave rectifier. Better results can be achieved when better rectifiers are employed.

However, when employing this approach, the responsibility for the accuracy of the measurement is transferred to the amplifier with a controlled gain that must show accurate gain setting according to the controlling signal generated by the microcontroller. Currently, an attempt of employing a digital potentiometer in the amplifier design is in progress.

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