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Simulation of Utility Losses Caused by Nonlinear Loads at Power Grid

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Abstract: This paper quantifies losses in a utility system caused by nonlinear loads. Distortion power is considered as a quantity that reflects the best effects of the losses. These losses are caused by nonlinear loads which are connected to the grid. The paper gives a review of trends related to changes of the character of loads connected to the utility together with its effects. The major problem reflects in the form of losses that utility register due to inadequate measurement equipment. We analyze core of the problem and suggest the solution that is verified by appropriate model and simulation. The method is suitable for implementation in electronic smart meters. This is confirmed by an upgrade of DSP dedicated for power/energy calculation within an original solid-state power meter. The enhanced version of DSP is designed in CMOS 0.35μm technology, using Cadence design tools for designed ASIC circuit.

Key Words: Distortion power, utility, power losses

I. INTRODUCTION

Classic approach to power metering and billing in households relays on registration of active power. It was sufficient in systems with dominant linear resistive loads (electric stove, water heater, electric furnace, incandescent bulbs). The active power is by definition:

$$P = V_{\mathrm{RMS}} I_{\mathrm{RMS}} \cos(\theta) \tag{1}$$

It has been supposed that large reactive loads exist in industry (predominantly the inductive motors). Therefore power meters aimed for industrial applications were capable to measure active and reactive power. The reactive power by definition is:

$$Q = V_{\mathrm{RMS}} I_{\mathrm{RMS}} \sin(\theta) \tag{2}$$

Electromechanical meters have bandwidth limitation. Therefore they cannot take into account harmonics [1].

The rapid development of electronics has changed the profile of the common customer's load. Electronic equipment has become dominant consumers. Their characteristic is to operate on small (<5V) DC voltage while supplied from AC 240V RMS. In order to increase efficiency of rectifiers and voltage regulators their operation frequency is moved from 50Hz to several kHz. Consequently this caused decreased dimensions of passive reactive components. Moreover, in order to diminish losses on active elements, transistors operate in the switch mode. All desired effects were obtained: effectiveness of rectifiers and regulators were considerably improved. As result more power goes to the loads (electronic equipment) and less dissipate on AC/DC convertors. However a small problem aroused. All such loads introduce large nonlinear distortion current that produce higher voltage drop in power line. The number of nonlinear loads has increased according to the tremendous rise of electronics appliances. Therefore, the level of power consumption at nonlinear loads becomes comparable in value with the linear.

The inert power system could not follow the development of electronics and even did not pay attention to possible consequences. The largest two blackouts in North American history (1965 and 2003) demonstrate sensitivity of the power system to small unjustly neglected problems. According to [2] "Both blackouts were the result of cascading failures of the power system, in which seemingly small and localized problems caused the system to become unstable and subsequently affect a much wider area." The current status in Serbia is that utility still uses electrical power meters capable to register only active energy consumption. Moreover, recently published tenders for new electronic power meters does not requests measurements of non-active components of power. The advantage options are required only from industrial power meters.

This paper is aimed to show the real consequences of using obsolete meters to register contemporary consumption. The subsequent section gives definitions of power components that appear in the grid in presence of the nonlinear loads. As one will see instead of active and reactive components, the apparent power contents additional component that is caused only by harmonics in nonlinear loads. This component is known as *distortion power*. It is important to stress that it could have value comparable to the active power and even to exceed it. Therefore, if the utility does not register this component it will have high level of losses.

The third section explains the effects of harmonics to the power system. The subsequent section describes the power meter model capable to deal with harmonic distortion. The fifth section presents simulation results. The architecture of DSP dedicated for energy metering in power meter is presented in sixth section before conclusion.

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II. COMPONENTS OF POWER IN DISTORTED SYSTEMS

Traditional power system quantities such as RMS values of current and voltage, power (active, reactive, apparent) are defined for pure sinusoidal condition. Due to harmonic distortion of current and/or voltage the definition of all power components have to be modified. The effect of harmonics must be taken into account. In case when harmonics exist in the power supply system, the instantaneous values of voltage or current can be express as:

$$x(t) = \sum_{h=1}^{M} X_h \sin(\omega_h t + \alpha_h) \qquad (3)$$

where h is the number of harmonic, M denotes the highest harmonic, while X_h , α_h, represent amplitudes and phase of signal. Frequency of the h^{th} harmonic is ω_h. RMS value of signal expressed by Eq. (3) is defined as:

$$X_{\text{RMS}} = \sqrt{\sum_{h=1}^{M} X_{\text{RMSh}}^2}\ , \qquad (4)$$

where X_{RMSh} is the RMS values of the h^{th} harmonic of the voltage or current. Product of the voltage and current at the same harmonic frequency gives the harmonic power. Total active power is defined as:

$$P = \sum_{h=1}^{M} V_{\text{RMS}_h} I_{\text{RMS}_h} \cos(\theta_h)\ . \qquad (5)$$

It could be presented as a sum of components related to the fundamental and other harmonics:

$$P = P_1 + P_{\text{H}}\ , \qquad (6)$$

where P_1 denotes contribution of the fundamental harmonic *(*h*=1)* and therefore named *fundamental active power* component; P_{H} comprises the sum of all higher components *(*h*=2,…*M*)* and is referred to as *harmonic active power*.

According to Budeanu the reactive power is defined as:

$$Q_{\text{B}} = \sum_{h=1}^{M} V_{\text{RMS}_h} I_{\text{RMS}_h} \sin(\theta_h) = Q_1 + Q_{\text{H}} \qquad (7)$$

where, similarly to Eq. (5), Q_1 and Q_{H} denote *fundamental reactive power* and *harmonic reactive power*, respectively.

Many authors claimed that the Budeanu's definition is not correct and cannot be used for calculating reactive power. However, this definition still occupies a significant number of pages on *The IEEE Standard Dictionary*, [3]. Its heritage is hard to dispute. Almost all contemporary textbooks written by appreciated scientists are to present Budeanu's definition of apparent power as the right canonical expression. More about calculating reactive power can be found in [3]

The vector sum of active and reactive power represents phasor power:

$$S = \sqrt{P^2 + Q^2}\ . \qquad (8)$$

However, this stands only for sinusoidal conditions. In presence of harmonics it is applicable to each harmonic component of active and reactive power separately [4]. Therefore, it will not be equal to the apparent power what applies in the case of sinusoidal condition. The difference reflects through the distortion power D. Consequently, the apparent power U (physically known as the product of RMS values of voltage and current) represents a vector sum of phasor power and distortion power [5]:

$$U = I_{\text{RMS}} * V_{\text{RMS}} = \sqrt{S^2 + D^2} \qquad (9)$$

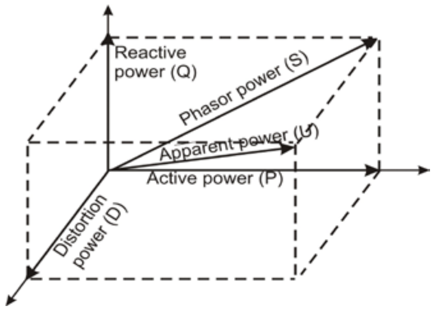


Fig. 1. Geometrical representation of relationship between active, reactive, phasor, distortion and apparent power, [5].

Fig. 1 illustrates relationship between active P, reactive Q, phasor S, distortion D and apparent power U, in monophase system with harmonic pollution. Obviously, Fig. 1 together with Eq. (8) and Eq. (9) express the fact that in unpolluted condition the distortion power will be equal to zero and apparent power U will be equal to phasor power S.

III. EFFECTS OF HARMONICS TO THE POWER SYSTEM

Electrical equipments, depending on the function they perform, react differently to harmonic distortions of the supply voltage. The distorted voltage has no effect to light bulbs but there is a large group of equipment which operating function relays on sine-wave voltage supply. Their best representatives are induction motors. Any deformation in voltage waveform introduces loss in form of increased coil temperature. Undoubtedly this reduces the life of the motor [6].

Besides, wide class of equipment that utilizes thyristor based control requires very precise supply voltage. Harmonic distortion may cause a malfunction of the apparatus.

The neutral line current in a three-phase power system may exceed the value of active power line. In single phase system the harmonic distortions raises a risk of overloading the neutral line. This usually causes:

- Overheating of neutral line, with reducing the life span of the conductor and with possibility to cause fire.
- High voltage between neutral line and ground can affect the operation of digital equipment and local area network (LAN), if the grounding is bad [9].

Harmonic distortions degrade power system characteristics and jeopardize all its components.

The distortion current causes additional heating of transformer and therefore reduces their lifespan. On the other hand, when distortion voltages are present in supply voltage for capacitor batteries, dielectric is overheating and threats to explode. Detail information about problems caused by harmonics can be found in [6], [7], [8].

IV. BEHAVIORAL POWER METER MODEL

Integrated power meters relay on digital signal processing of voltage and current samples. Therefore accurate modelling requires discrete-time models of all power components. Instantaneous value of current or voltage in time domain describe equation:

$$x(t) = \sqrt{2} X_{RMS} \cdot \cos(2\pi f t + \varphi) \ . \qquad (10)$$

After the discretization in equidistant time intervals it transforms to:

$$x(nT) = \sqrt{2} X_{RMS} \cdot \cos(2\pi \frac{f}{f_{sempl}} n + \varphi) \ , \qquad (11)$$

where f and f_{sempl}, are frequency of the signal and the sampling frequency. By definition the RMS value is:

$$X_{RMS} = \sqrt{\frac{\sum_{n=1}^{N} x(nT)^2}{N}} \ . \qquad (12)$$

The active power is obtained as average of the instantaneous multiplication of instantaneous values for current and voltage, and average active power one gets in form:

$$P = \frac{\sum_{n=1}^{N} v(nT) i(nT)}{N} = \frac{\sum_{n=1}^{N} p(nT)}{N} . \qquad (13)$$

The same model is used for reactive power after voltage samples are shifted for $\pi/2$. Possible sources of error in active and reactive power calculation are caused with the phase difference between voltage and current and the fact that the power line frequency is slightly changed around the nominal (50Hz). These errors can be eliminated/diminished by additional calibration and correction within appropriate filters.

Once when P is calculated according to Eq. (13), Q calculated on similar way using shifted voltage samples, and U obtained as the product of RMS of voltage and current Eq. (9), one easily can compute distortion power as:

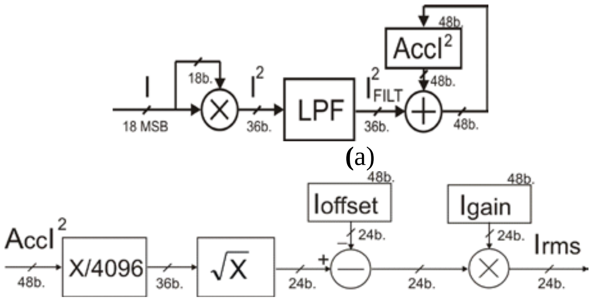
$$D = \sqrt{U^2 - P^2 - Q^2} \ . \qquad (14)$$

The previous equations represent bases for RTL model development of a power meter.

Firstly it was implemented in Matlab. Simple numerical integration of P, Q, U, D and S in time gives appropriate energies.

The part that calculates I_{RMS} (and V_{RMS}) has already been developed in LEDA laboratory for previous versions of our solid state power meter named IMPEG [10], [11].. It is presented in Fig. 2. Blocks denoted as I_{offset} and I_{gain} are used to compensate the errors described above.

In order to calculate D, the model has been modified as Fig. 3 presents. It consists of the multiplayer, the accumulator, the square-root and the finite-state-machine block.



(a)

(b)

Fig. 2.Block diagram of the model for I_{RMS} (and V_{RMS}) calculation using Eq. (12)

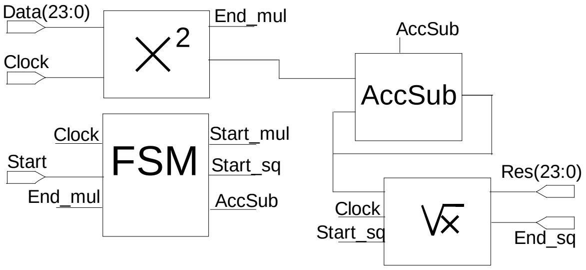


Fig. 3. Block diagram of model for calculating the distortion power

The model is based on multiply implementation of block diagram in Fig. 3. Practically model calculates I_{RMS} and V_{RMS} when $i(nT)$ or $v(nT)$ are supplied to Data input. Model for P differs only in feeding multiplier with both $i(nT)$ and $v(nT)$.

Model for Q has identical structure but it is fed with voltage samples displaced for $\pi/2$.

Apparent power samples are calculated directly applying Eq.(9).

The multiplier accepts samples of the apparent power U trough Data port. After 24 clock cycles required for 24-bit signal using Booth's algorithm the squared value of the apparent power U^2 appears and being stored. Thereafter the value of the active power is squared and the new value is subtracted from the value of apparent power. The same process is repeated for reactive power Q. Finally, the obtained value is sent to the input of the square root block that provides distortion power *D*. FSM block provides control signals that schedule correct operation.

The model was confirmed by simulation. Moreover it has been verified on prototyped power meter realised by EWG electronics [12]The prototype has been developed using the electric power meter that was based on standard IC 71M6533 manufactured by MAXIM. Consequently it already provided I_{RMS}, V_{RMS}, *P* and *Q*. on the same manner as Eq. (12) and Eq. (13) describe. Thereafter *U* and *D* were calculated according to Eq. (9) and Eq.(14).

V. SIMULATION RESULTS

We used the developed model to simulate different types of non-linear loads. In order to approve both the method for distortion power calculation and the model we used measured data for currents published in [8], [13]. Fig. 4 illustrates the appropriate waveforms.

In order to simulate a possible realistic case, we supposed that the voltage is polluted, as well. Namely it has 3^{rd} harmonic with amount of 3% in respect to the fundamental component. We considered eight different types of loads connected to the grid. There are:

a) Incandescent light bulb (ILB)
b) Heater (HR)
c) Fluorescent lamp (FL)
d) EcoBulb Compact Fluorescent Lamp (ECFL)
e) Phillips Compact Fluorescent Lamp (PCFL)
f) 6-pulse 3-ϕ diode rectifier dc power supply (3-DR)
g) 6-pulse switched-mode power supply (SMPS)
h) 6-pulse PWM controlled variable speed drive (PWM VSD)

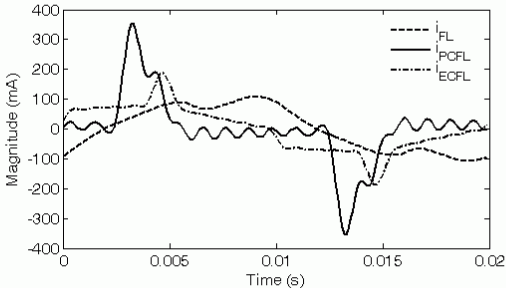


Fig. 4.a. Current waveforms for Fluorescent lamps: FL, ECFL and PCFL

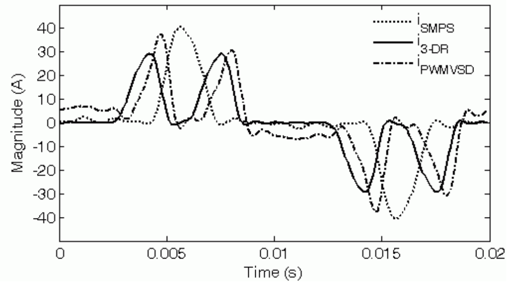


Fig. 4.b. Current waveforms for Rectifiers: 3-DR, SMPS and PWM VSD

The first two cases represent linear loads. Therefore the obtained current follows the voltage waveform. All other loads are nonlinear. Consequently they draw distorted current. Fig. 4.a illustrates currents of FL, ECFL and PCFL. Fig. 4.b presents waveforms of currents through 3-DR, 6-SMPS, and PWM VSD. Table I summarizes the obtained results.

TABLE I

SIMULATION RESULTS FOR DIFFERENT TYPES OF LOADS

	ILB	HR	FL	ECFL	PCFL	3-DR	SMPS	PWM VSD
I_{RMS}[A]	0.434	10.01	0.103	0.091	0.129	13.5	14.8	14.2
V_{RMS}[V]	230.3	230.3	230.3	230.3	230.3	230.3	230.3	230.3
P[W]	99.8	2305.0	17.32	18.49	15.85	2251.4	2183.9	2305.2
Q_{B}[VAR]	0	0	15.37	-5.99	-9.3	470.3	412.3	-8.96
U[VA]	99.8	2305.8	23.6	20.9	29.7	3115.4	3416.9	3277.1
D_{B}[VAR]	0	0	4.64	7.73	23.3	2101.4	2595.3	2329.3
D_{B}/P[%]	0	0	26.79	41.81	147.00	93.34	118.84	101.05
(U-P)/P [%]	0.00	0.03	36.26	13.03	87.38	38.38	56.46	42.16
S [VA]	99.80	2305.0	23.16	19.44	18.38	2300.0	2222.4	2305.22
(S-P)/P [%]	0.00	0.00	33.70	5.12	15.94	2.16	1.77	0.00

As expected, for both linear resistive loads, the active power, *P*, equals to the apparent power, *U*. Therefore the distortion power calculated using Eq. (14) equals zero. The other cases with non-linear loads should result with non-zero distortion power. The currents of each load are very rich with harmonics. Therefore, I_{RMS} increases proportionally to harmonics and consequently *U* and D_B, rise, as well

Cases FL, ECFL and PCFL represent small loads, with *P*<20W. Fig.4.a suggests that the current waveform of the PCFL is the most distorted. Hence, we expect to get greater D_{B} then in case of FL and ECFL. The result of simulation listed in the row D_B in Table I confirms the expectation.

Large loads (*P* greater of 2kW) have much higher impact to the grid and deserve more attention. Fig.4.b indicates that the SMPS is the biggest source of harmonic pollution. Simulation results confirm this anticipation.

Obviously, the measure of the distortion power is in direct relation with the nonlinearity of a particular load. Losses caused by nonlinear loads expressed as distortion power could range up to 147% relative to the active power. This was the case for PCFL. However because of the low nominal active power of 16W this is not a treat for the utility at the household level. One should concern more about larger loads like 3-DR, SMPS and PWM VSD. Table I presents that the amount of the distortion power is comparable with the active power. Moreover it is greater than 2kW.

It is interesting to estimate losses that utility has only due to the lack of registration of distortion and reactive power. Therefore we present the ratio of the difference between apparent and active power and the active power. Obviously PCFL represents the worst case with losses of 87%. However due to relatively small nominal active power this has neglecting effect to the power system. In contrary larger loads produce greater losses. Table I indicates that the largest losses provide the device with the most high distortion level. Actually SMPS produces losses of 56% on the load of 2183W. On other two loads of comparable nominal power the utility has losses of 40%. These definitely are not negligible.

VI. DSP DEDICATED FOR DISTORTION POWER METERING

Block DSP represents a part of integrated power meter (IMPEG). Instantaneous values of current and voltage are obtained from digital filters and based on them on every second DSP calculates RMS value of current I_{RMS} and voltage V_{RMS}, active P, reactive Q , distortion D and apparent U power, power factor and frequency [10, 11]. Using value of active and reactive power DSP generate impulse for every Wh measured energy. This impulse increment register of DSP, that save information of active and reactive power (generated or consumed).DSP block work at 4.194 MHz and with accuracy less than 0.1% calculates all mentioned parameters. It accepts 16–bit wide inputs representing voltage, current and phase-shifted voltage samples from digital filters. Thereafter, it calculates already mentioned final power line parameters. Three sets of power line measurement results are obtained for different power line phases called R, S and T. The current input dynamic range is from 10 mA RMS to 100 RMS, while for voltage input it is up to 300V RMS. Results are represented within DSP by 24-bit 2’s complement values.

DSP utilizes controller/datapath architecture which consist of several blocks: finite state machines, three static single port 64x24 bit Random Access Memories, datapath registers, arithmetical units for addition, subtraction, division, square rooting, multiplication and other digital blocks. Digital blocks can be divided into five main groups (Fig. 1):

1. Frequency measurement circuit
2. RAM memory block
3. Part for I2, V2, P, Q accumulating and energy calculation
4. Part for current and voltage RMS, active, reactive , apparent and distortion power and power factor calculation);
5. Control unit that manages all other parts of DSP.

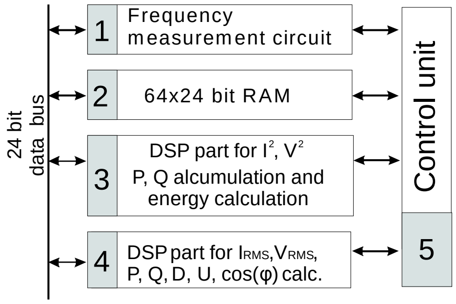


Fig.5 DSP block diagram

There is a single 24-bit data bus connecting these subblocks of DSP. The control path of DSP unit is implemented as a finite state machine and it generates a number of control signals that determine what component can write to 24-bit data, what registers are loaded from the bus and what arithmetical operation is performed. Controller performs the periodically repeated sequence that lasts exactly 1024 clock periods which is divided into four 256 clock period subsequences. The first three FSM subsequences are called R, S and T and they control the calculations made for each phase of the three-phase energy system. During R, S and T subsequences intensive calculations are performed only within subpart 3 (Fig.4). More detail about architecture of DSP can be found in [10] and [11].

VII. CONCLUSION

This paper presented a model for distortion power calculation. Simulation of six nonlinear and two linear loads verified the model. Moreover the results indicated that utility suffers large losses due to the lack of registering distortion power. Actually the utility in Serbia and in the greater part of the world relays billing only on active power measurements. However, for real cases of large nonlinear loads the losses overcome 50% in comparison to the active power. Having in mind that the number of nonlinear loads rapidly increases this amount rises with no visible ending in the near future. Therefore this seems to be a tremendous problem. It is interesting that some of developed countries recently has invested a lit of money to replace old power meters capable to measure only active power with the new that measure reactive power as well. According to [1] Italy distributor has decided to install more than 20 million household energy meters with active and reactive power measurement. However without measuring distortion power all this all of this misses the point. Two bottom rows in Table I represent the phasor power S (Eq. (8)) and the according losses calculated in respect to active power. The characteristic case is 6-pulse PWM controlled variable speed drive with the nominal active power of 2300W with small reactive power but with large distortion power. The relative loss regarding the phasor power is almost zero, but regarding the apparent power is 42%.

Obviously the utility will be faced very soon with a tremendous problem with losses if does not start to measure all power components. Some may argue that it is sufficient to register only the apparent power. However, this would be step back because contemporary power meters are capable to measure all components. As we have recently published [14] measuring distortion power at PCC helps the utility to determine the source of nonlinear pollution at the grid. Therefore it would be capable to bill separately every component of power. In our opinion this will cut the losses but will serve as mighty tool to manage the loading profile of the consumers.

ACKNOWLEDGEMENTS

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